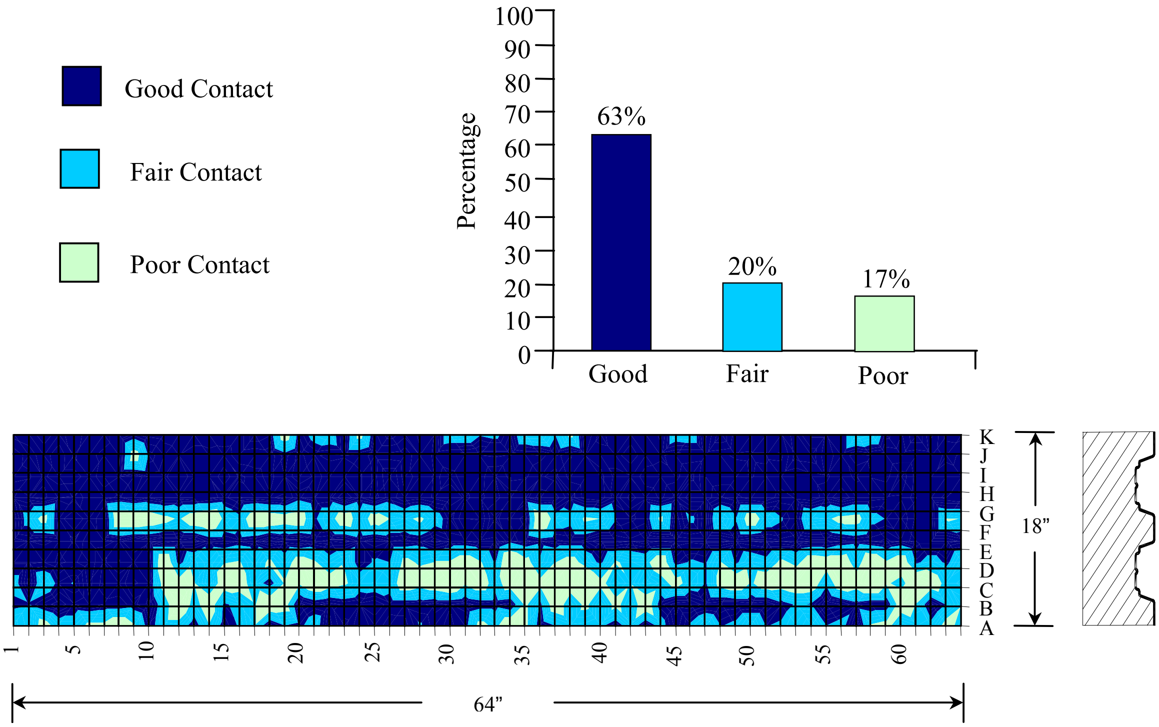


Figure 5.28. Pulse-echo contour map and bar chart
for Before Cracking for specimen WI-S-1-1

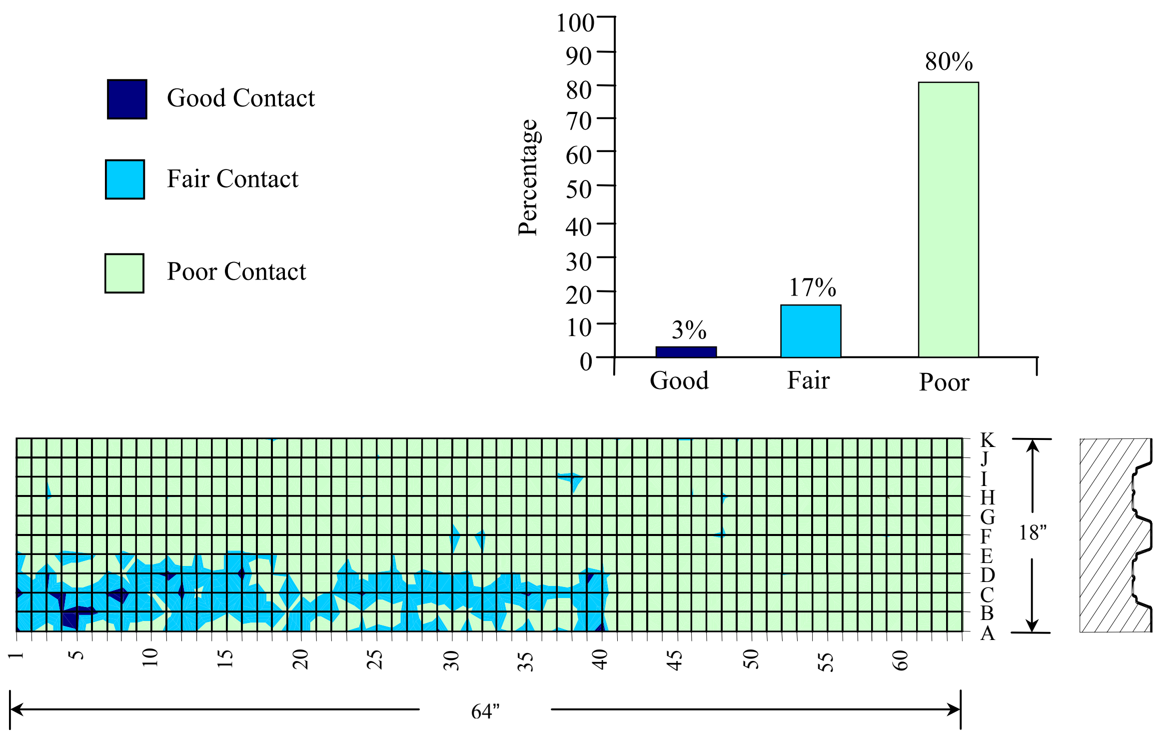


Figure 5.29. Pulse-echo contour map and bar chart
for After Cracking for specimen WI-S-1-1

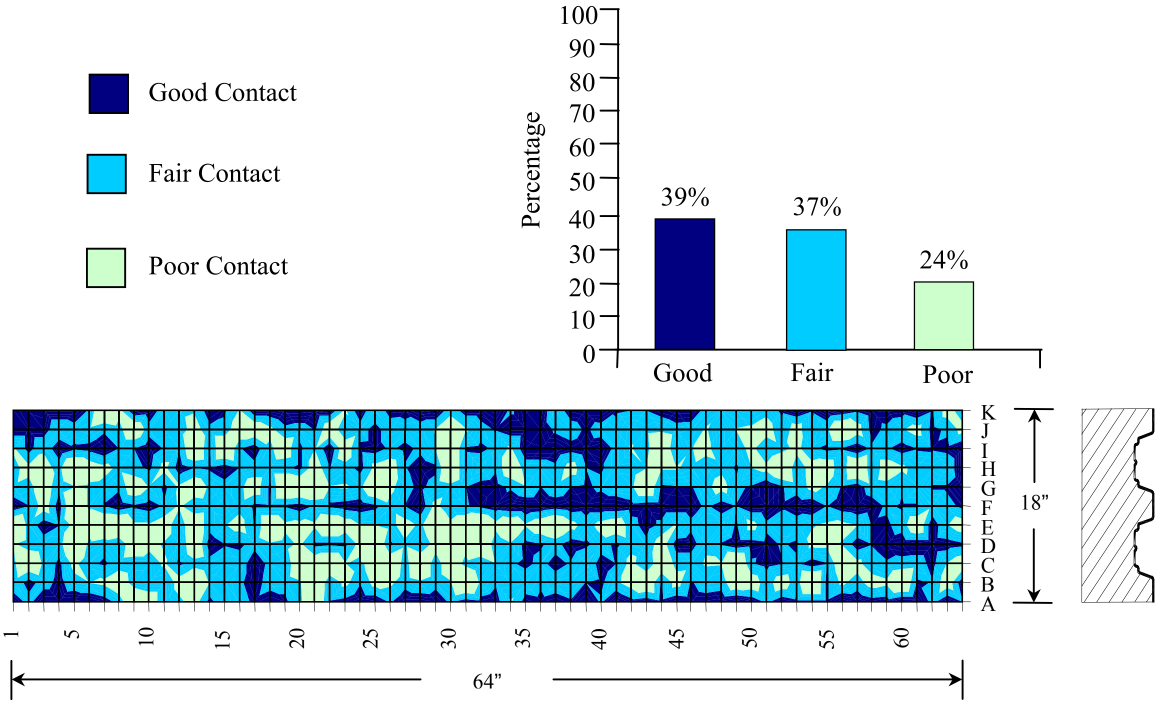


Figure 5.30. Pulse-echo contour map and bar chart
for After 1,000 hrs Salt-Water for specimen WI-S-1-1

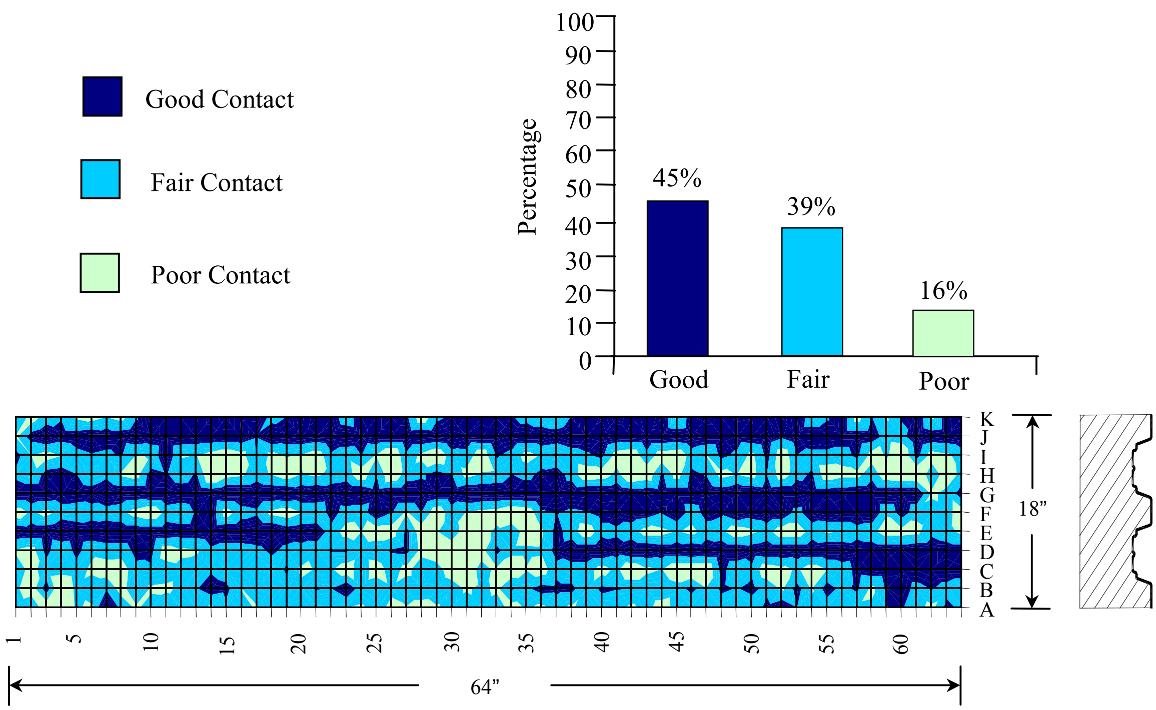


Figure 5.31. Pulse-echo contour map and bar chart
for Before Cracking for specimen WI-S-1-2

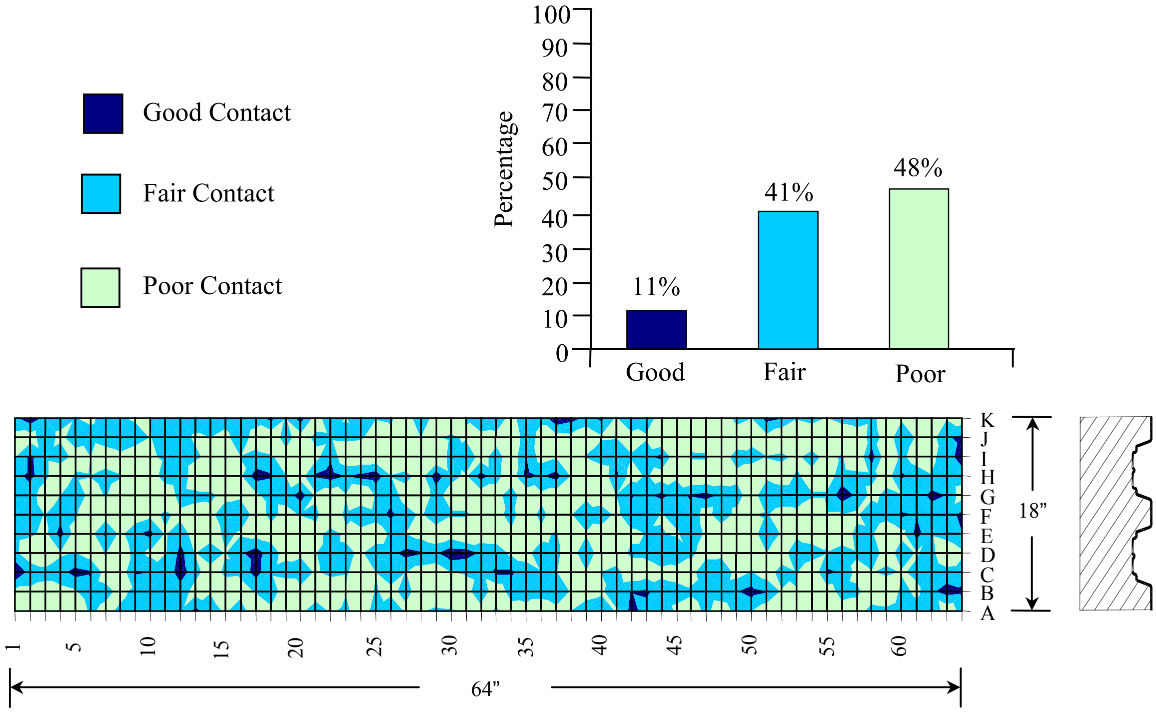


Figure 5.32. Pulse-echo contour map and bar chart for After Cracking for specimen WI-S-1-2

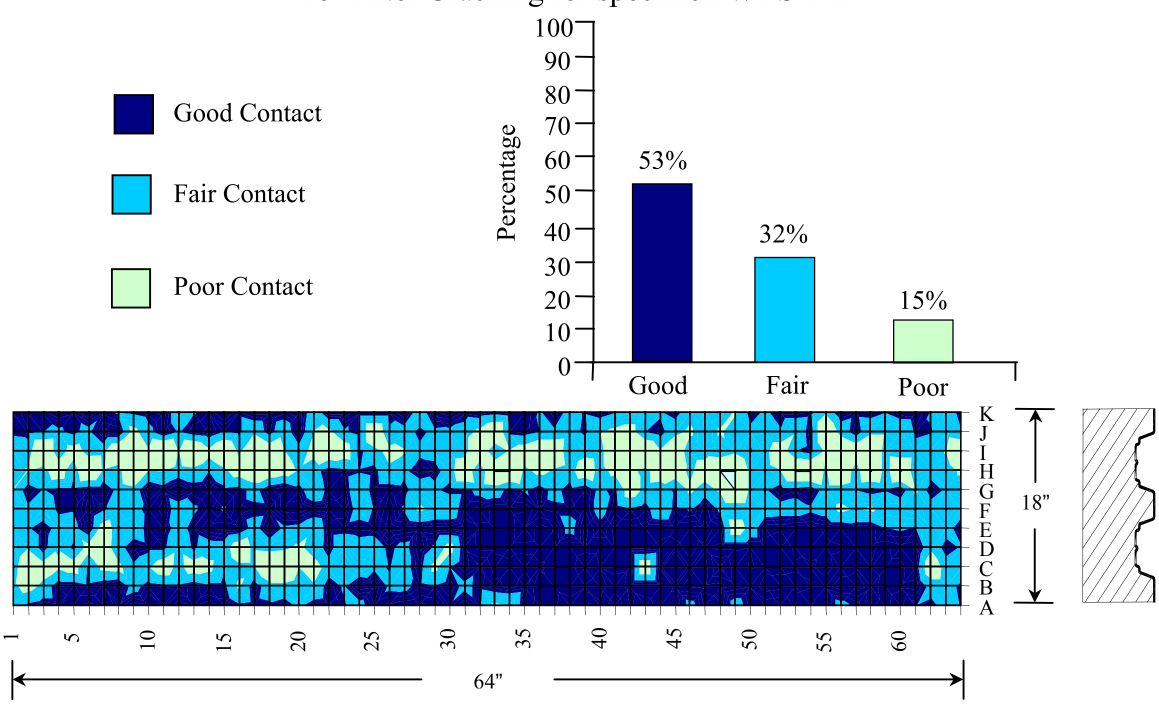


Figure 5.33. Pulse-echo contour map and bar chart for After 1,000 hrs Salt-Water for specimen WI-S-1-2

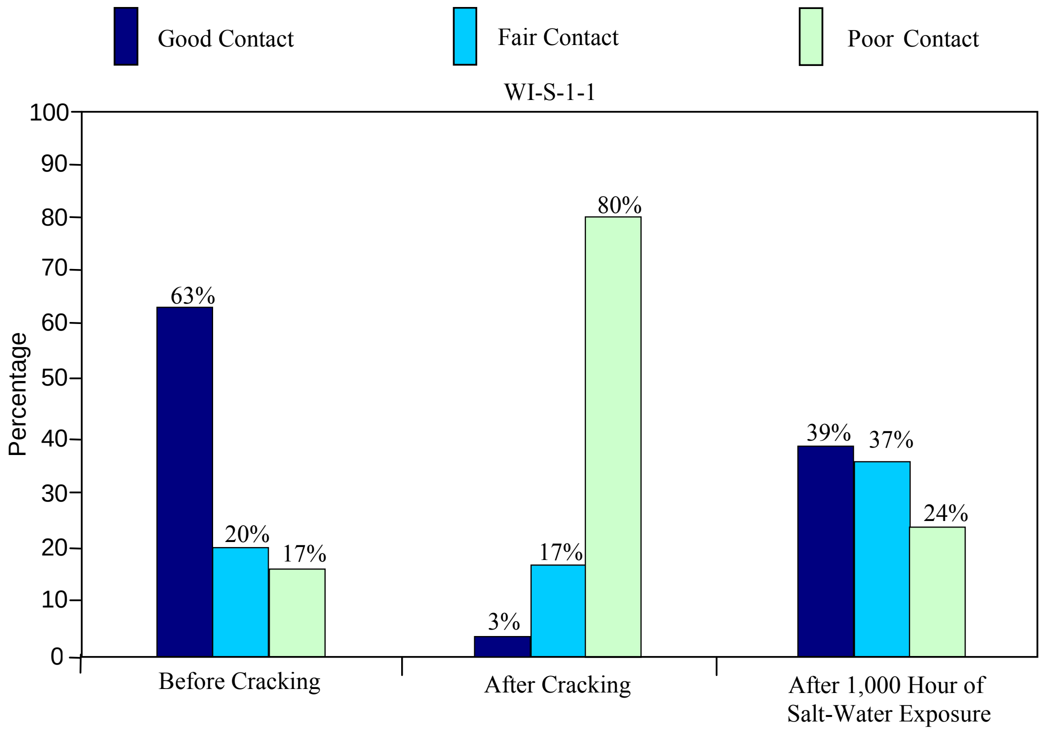


Figure 5.34. Summary of pulse-echo results for specimen WI-S-1-1

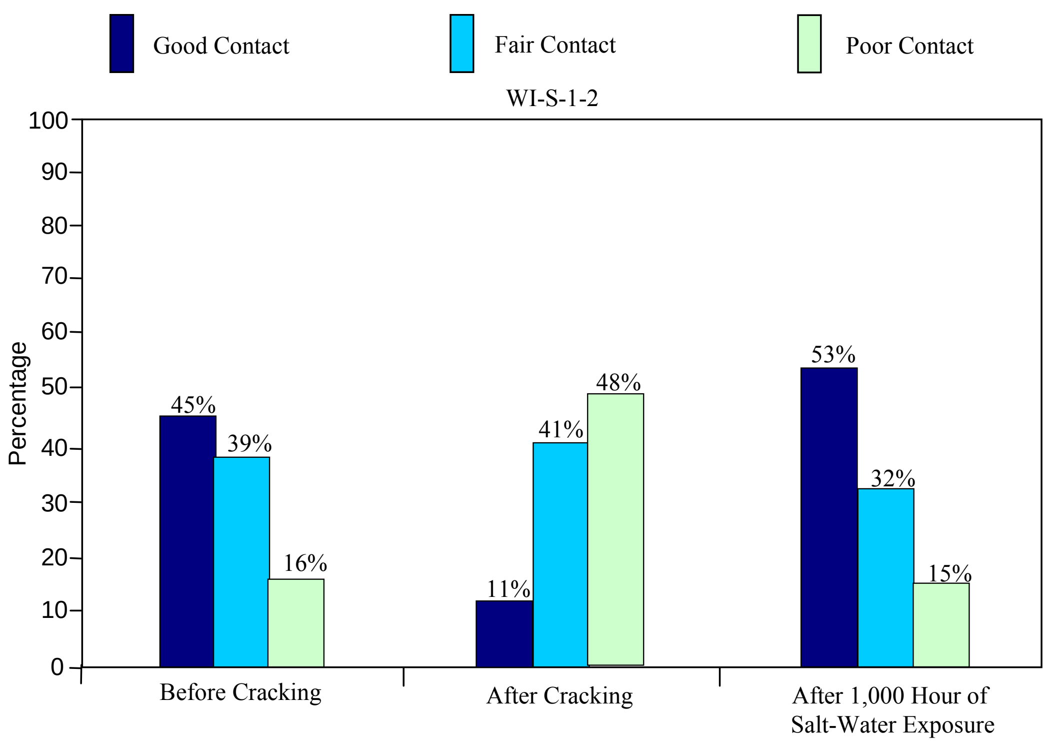


Figure 5.35. Summary of pulse-echo results for specimen WI-S-1-2

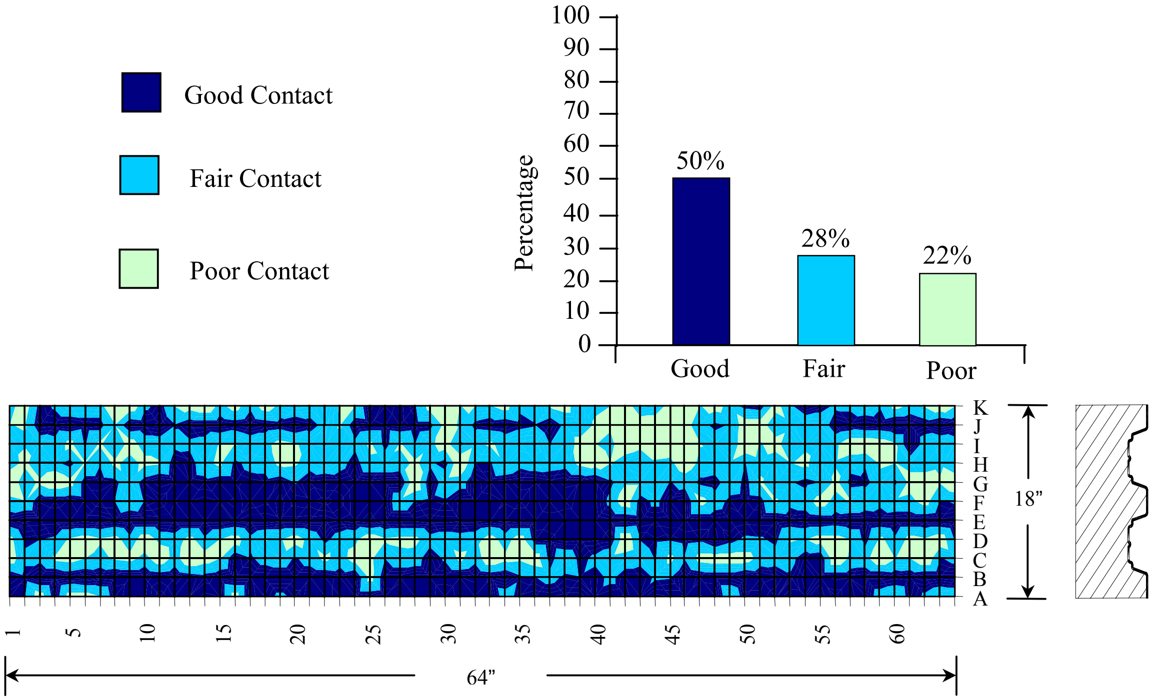


Figure 5.36. Pulse-echo contour map and bar chart for Before Cracking for specimen WI-S-3-1

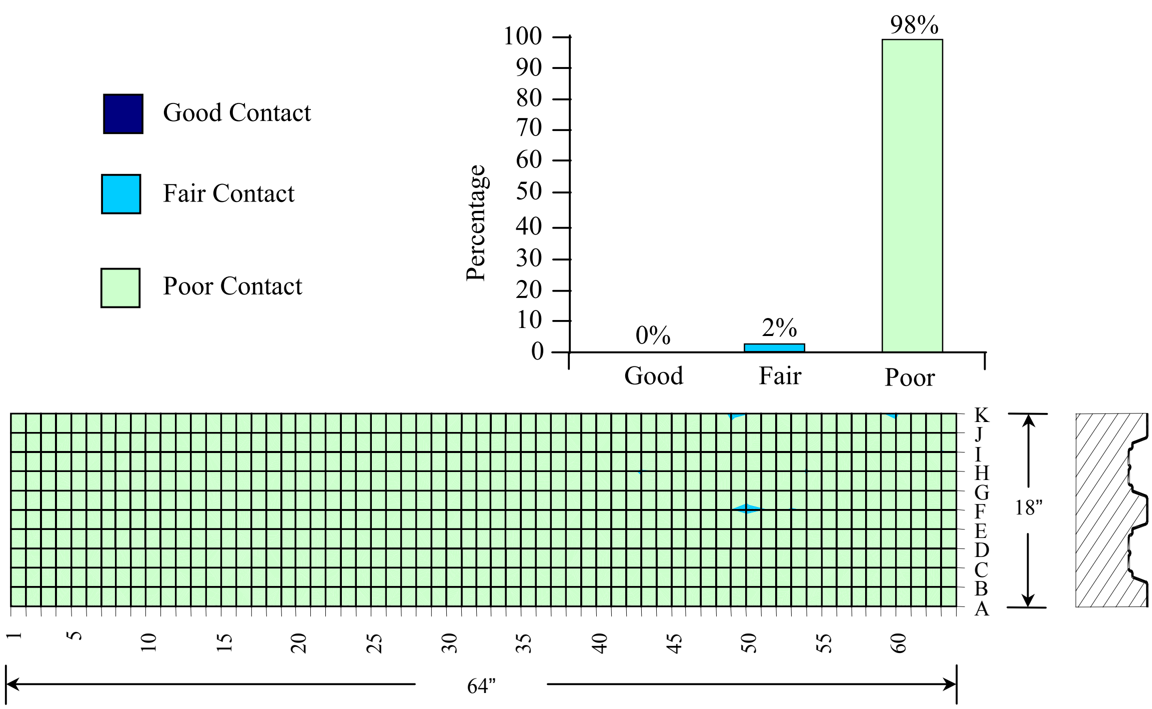


Figure 5.37. Pulse-echo contour map and bar chart for After Cracking for specimen WI-S-3-1

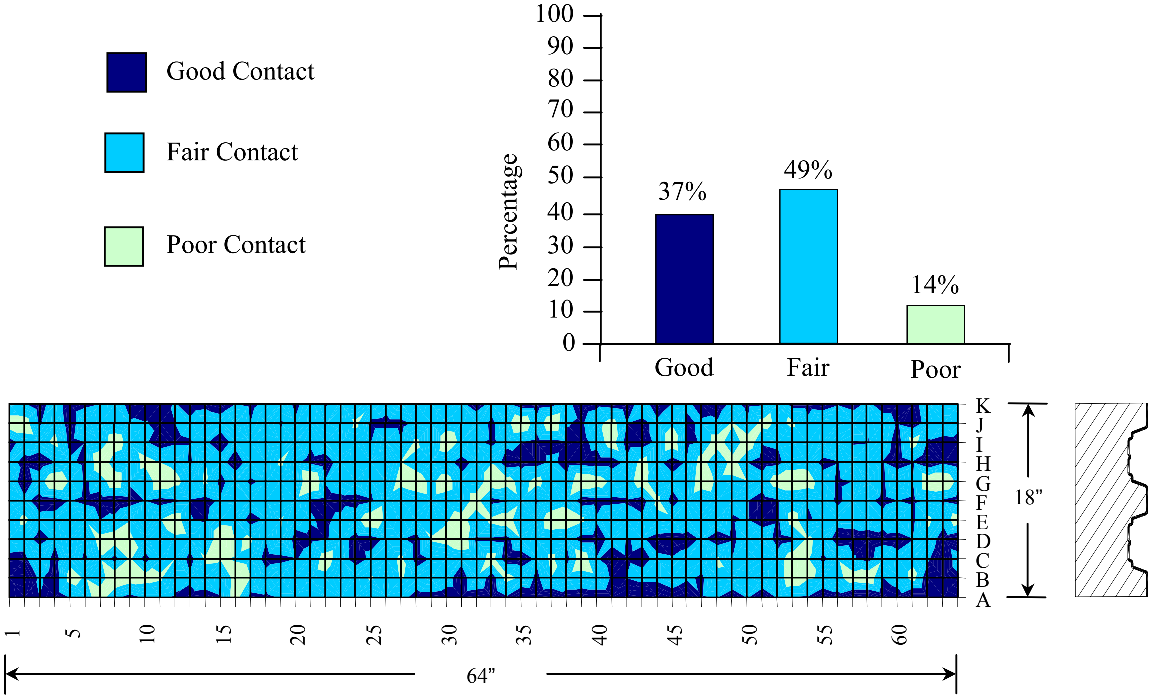


Figure 5.38. Pulse-echo contour map and bar chart
for After 1,000 hrs Salt-Water for specimen WI-S-3-1

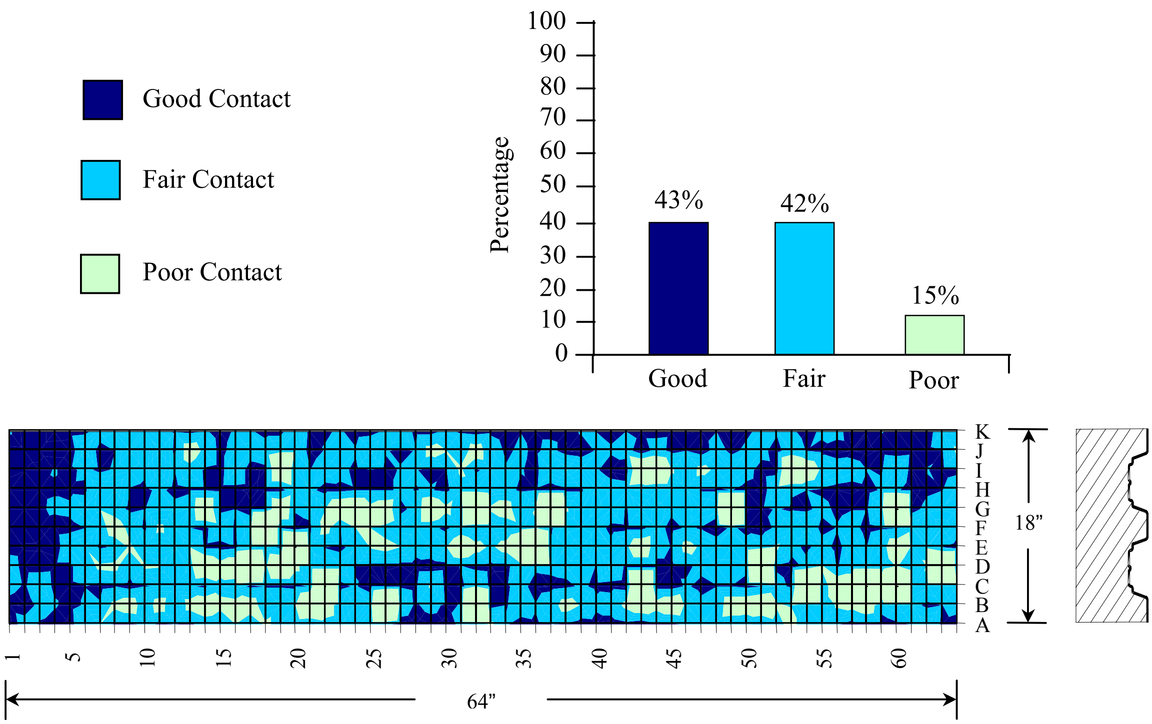


Figure 5.39. Pulse-echo contour map and bar chart
for After 3,000 hrs Salt-Water for specimen WI-S-3-1

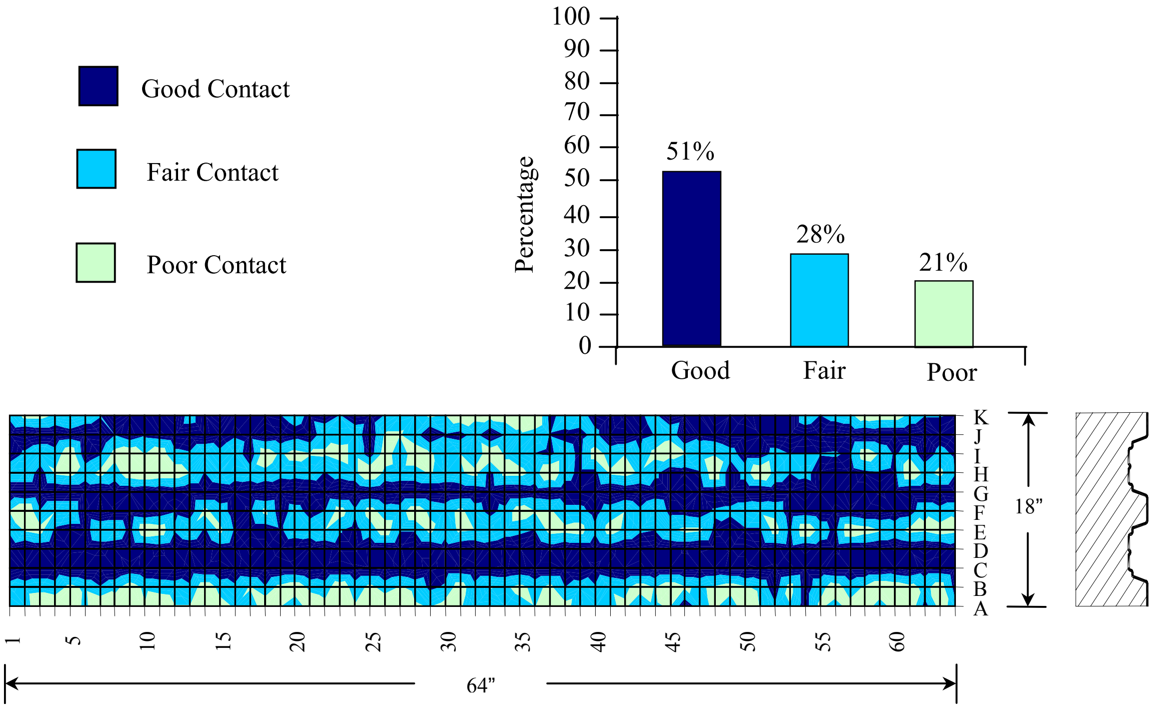


Figure 5.40. Pulse-echo contour map and bar chart
for Before Cracking for specimen WI-S-3-2

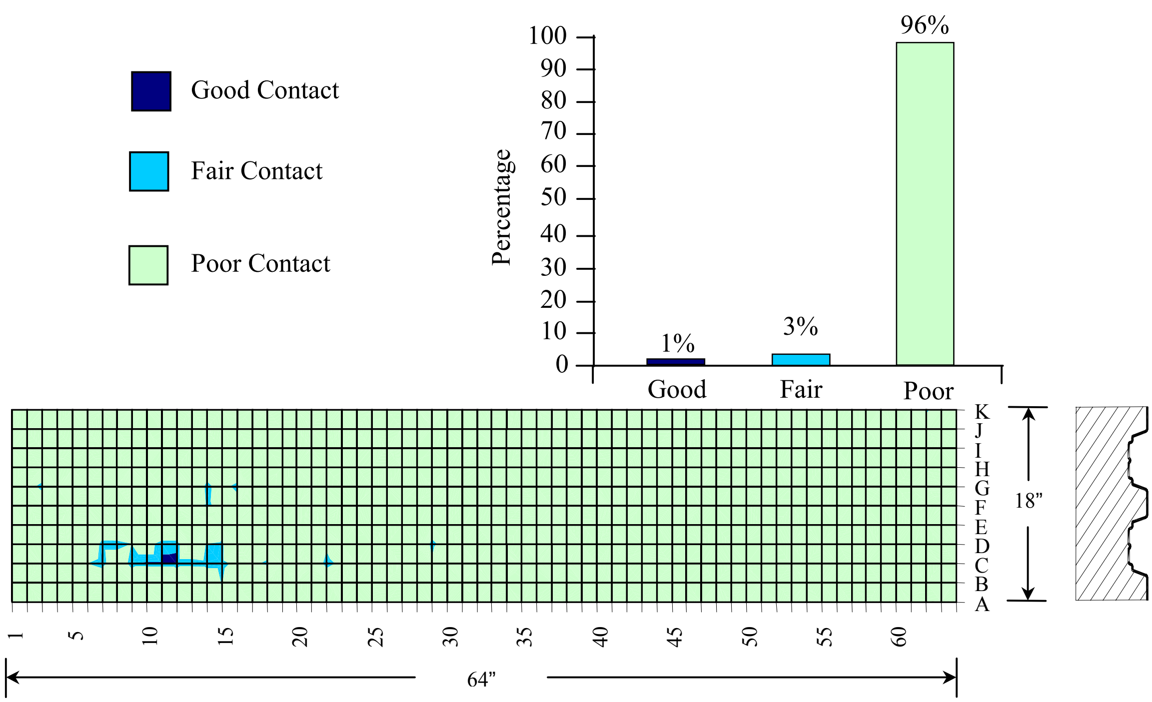


Figure 5.41. Pulse-echo contour map and bar chart
for After Cracking for specimen WI-S-3-2

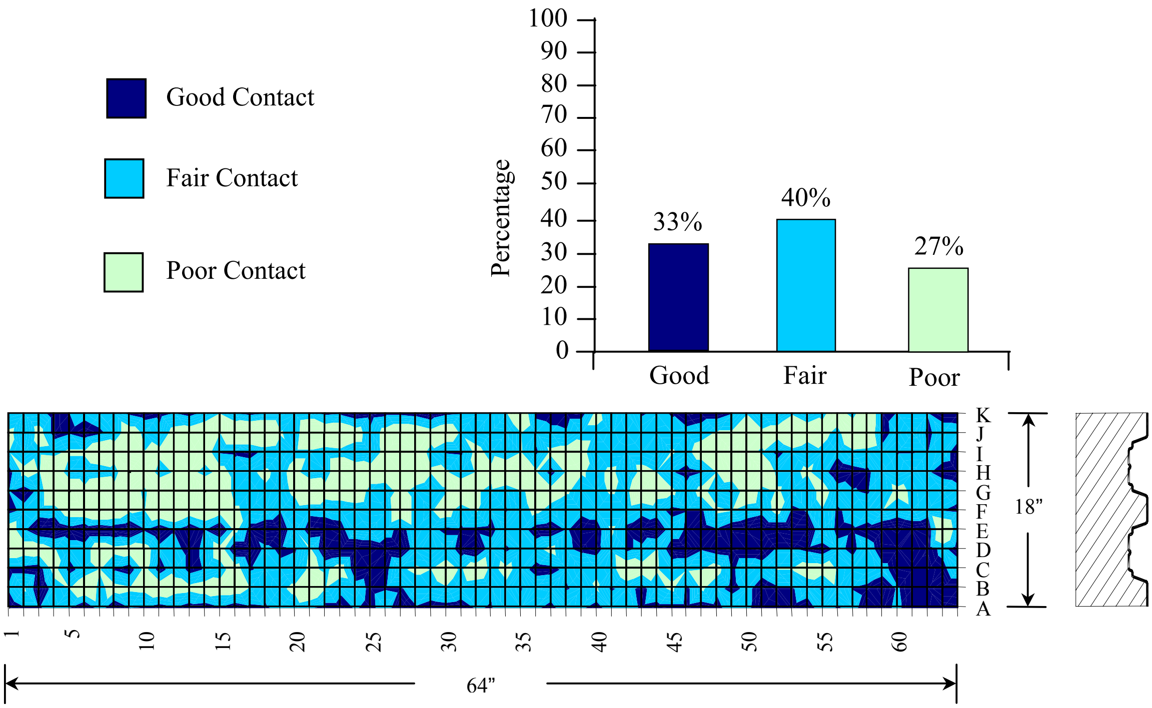


Figure 5.42. Pulse-echo contour map and bar chart
for After 1,000 hrs Salt-Water for specimen WI-S-3-2

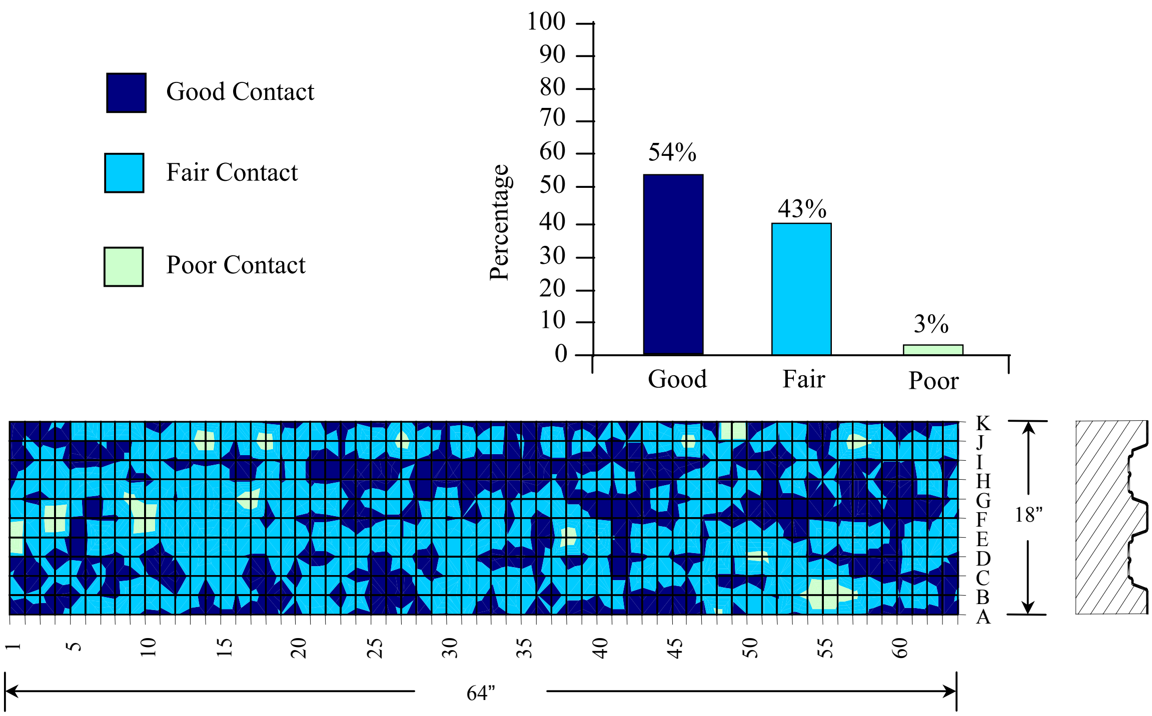


Figure 5.43. Pulse-echo contour map and bar chart
for After 3,000 hrs Salt-Water for specimen WI-S-3-2

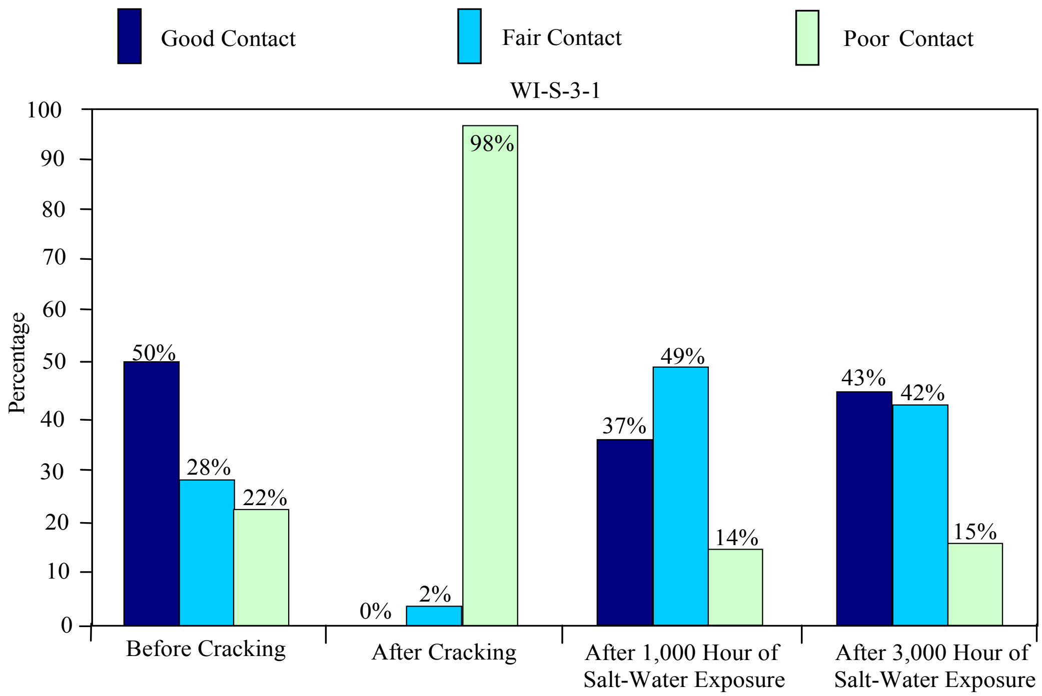


Figure 5.44. Summary of pulse-echo results for specimen WI-S-3-1

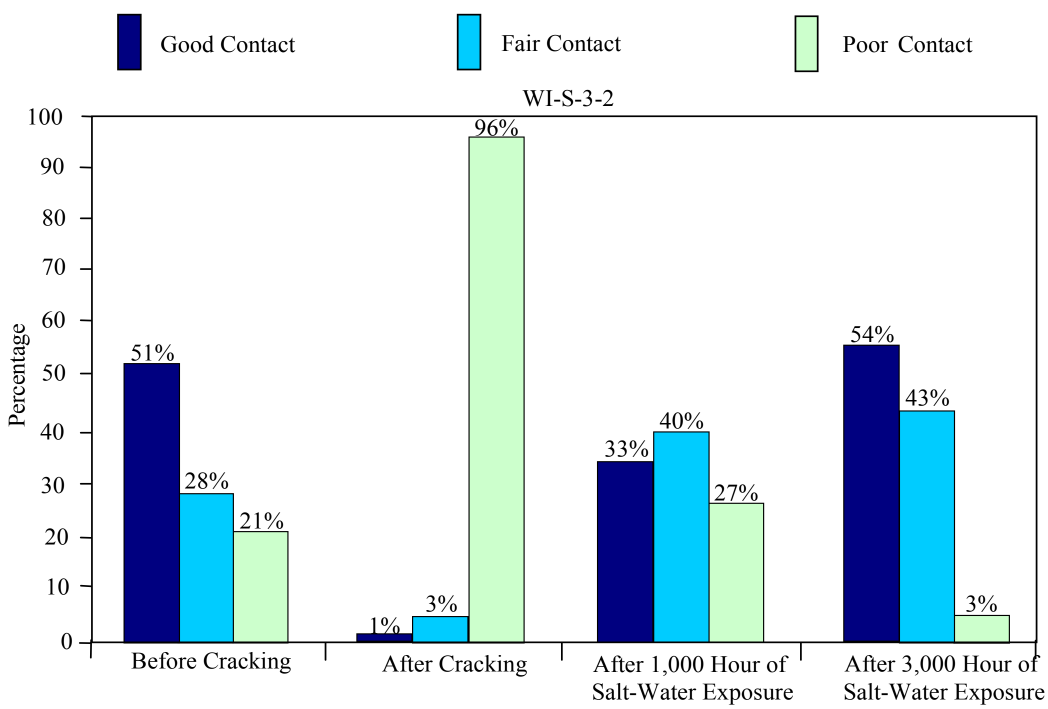


Figure 5.45. Summary of pulse-echo results for specimen WI-S-3-2

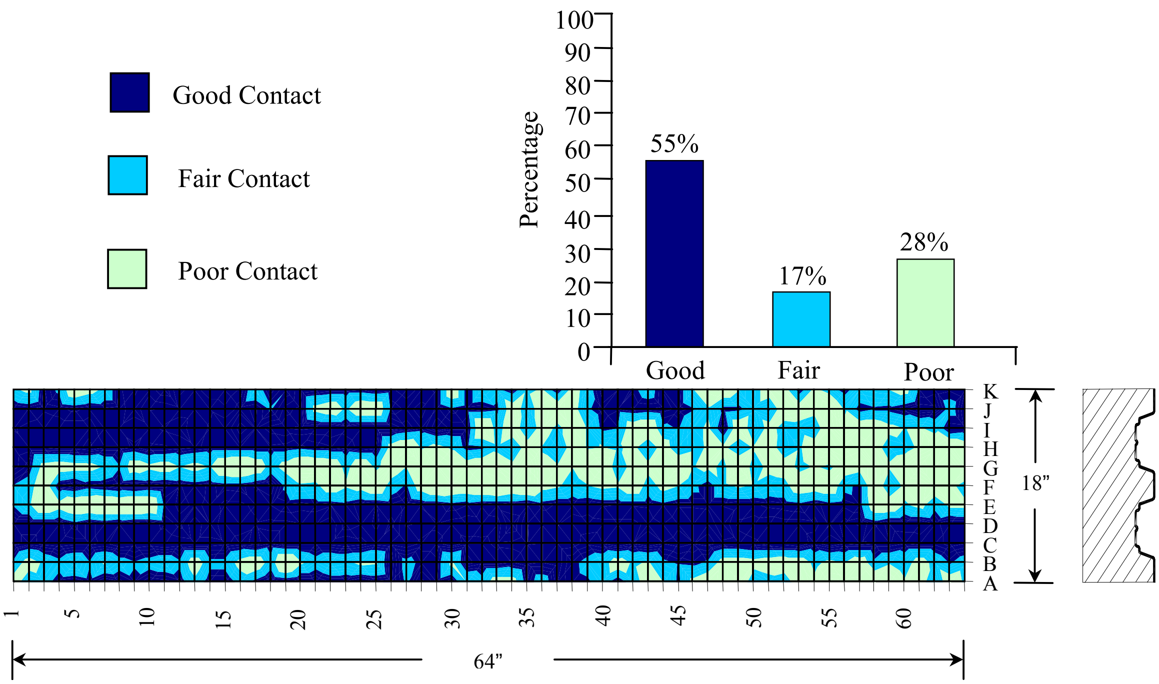


Figure 5.46. Pulse-echo contour map and bar chart for Before Cracking for specimen WI-S-10-1

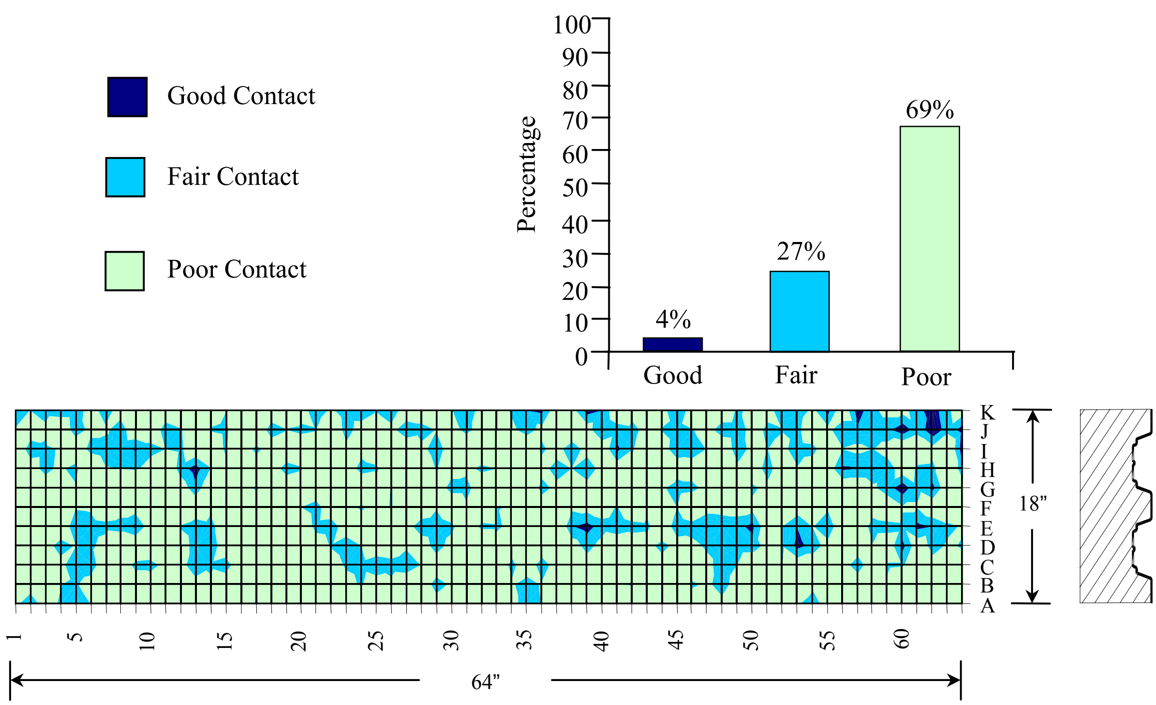


Figure 5.47. Pulse-echo contour map and bar chart for After Cracking for specimen WI-S-10-1

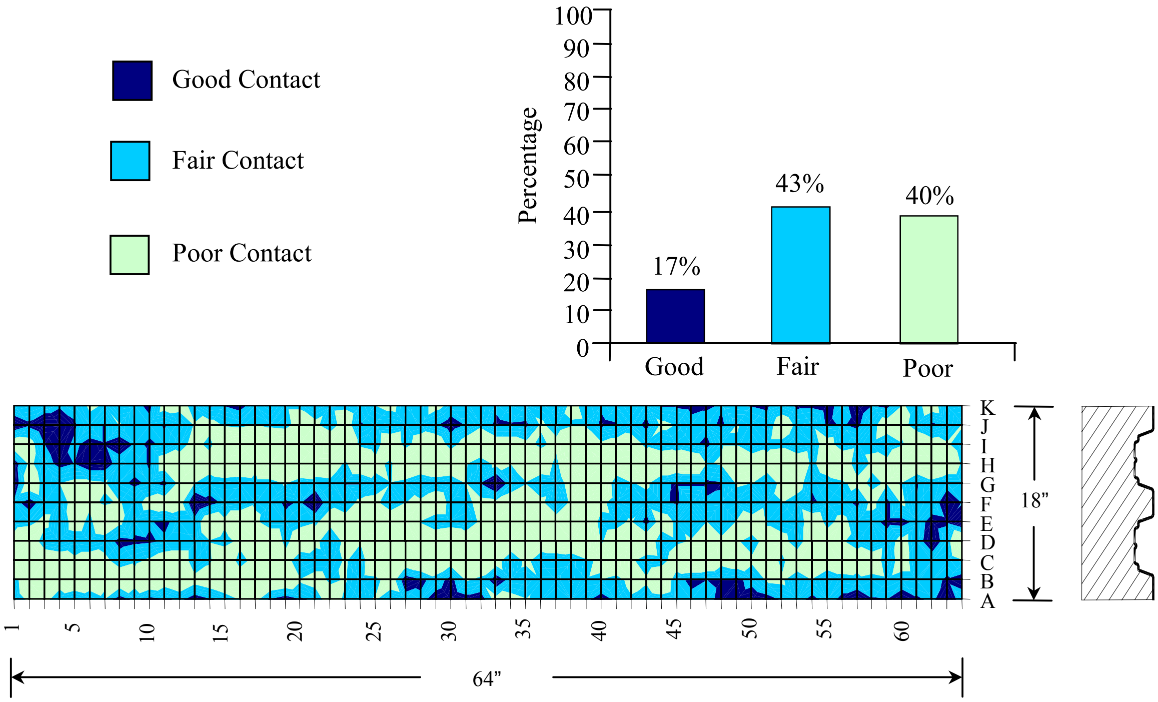


Figure 5.48. Pulse-echo contour map and bar chart
for After 1,000 hrs Salt-Water for specimen WI-S-10-1

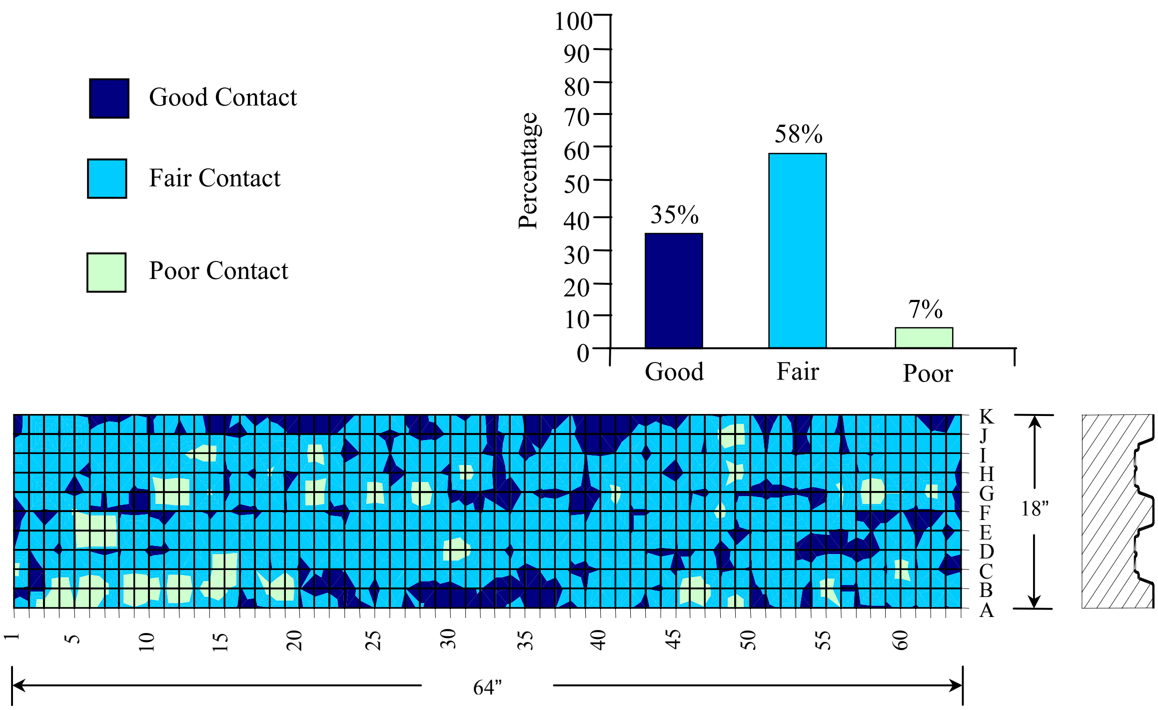


Figure 5.49. Pulse-echo contour map and bar chart
for After 3,000 hrs Salt-Water for specimen WI-S-10-1

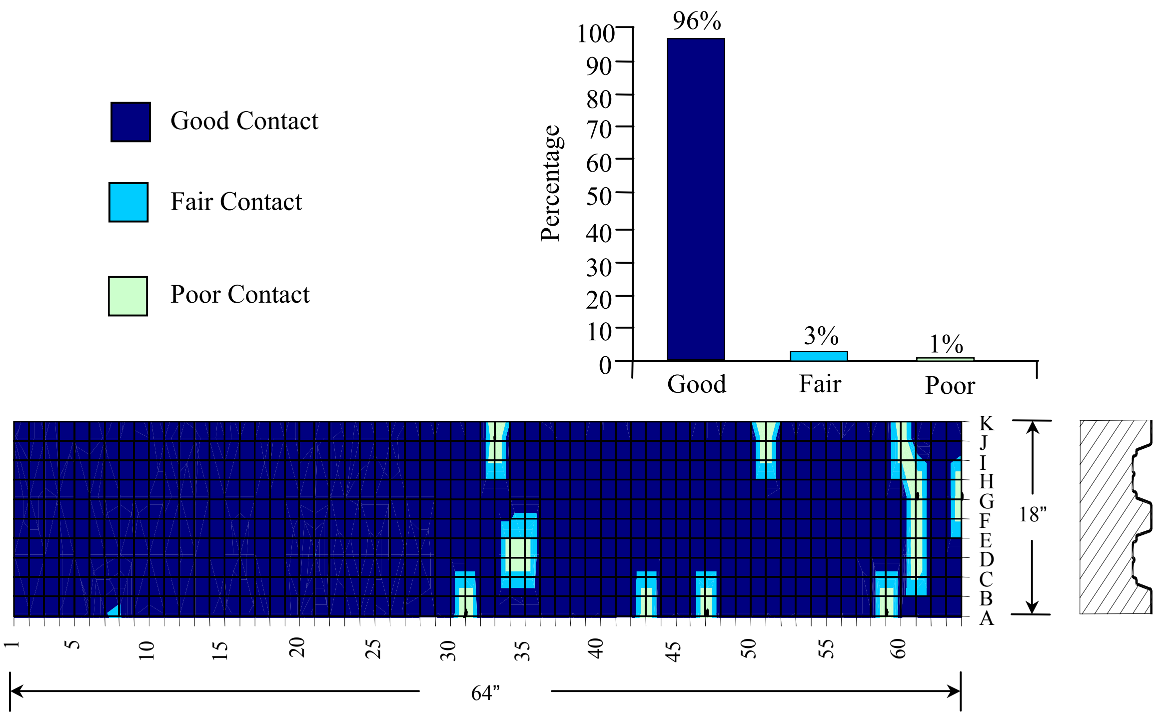


Figure 5.50. Pulse-echo contour map and bar chart
for After 10,000 hrs Salt-Water for specimen WI-S-10-1

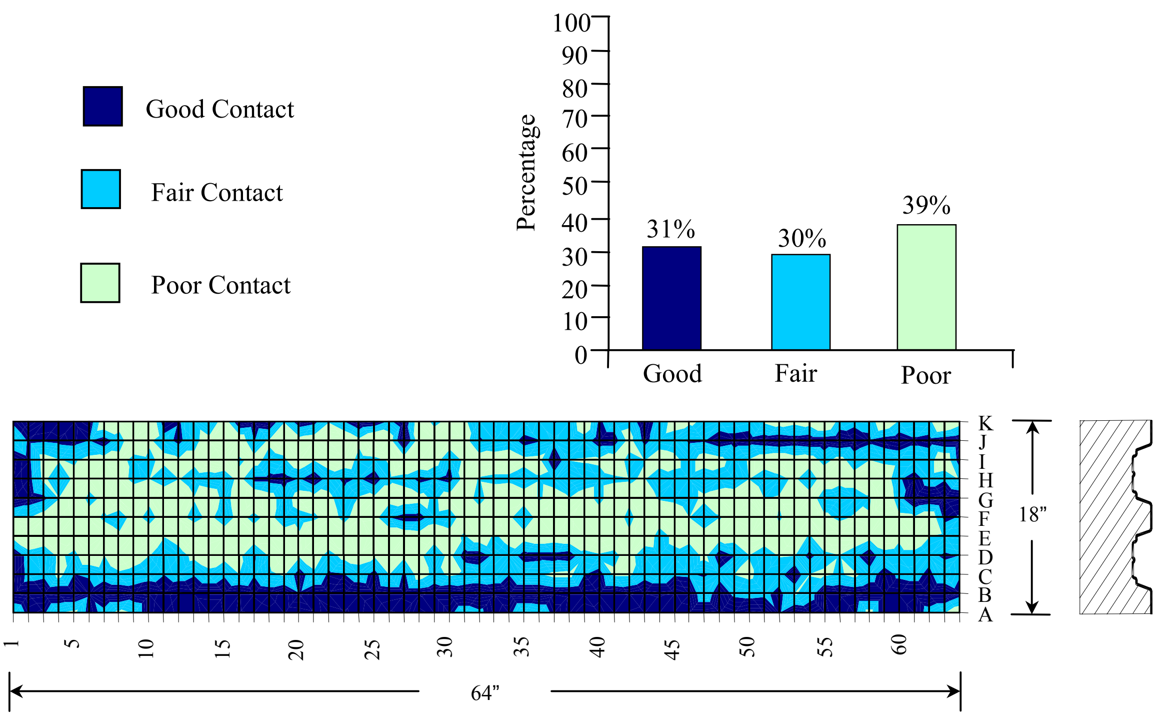


Figure 5.51. Pulse-echo contour map and bar chart
for Before Cracking for specimen WI-S-10-2

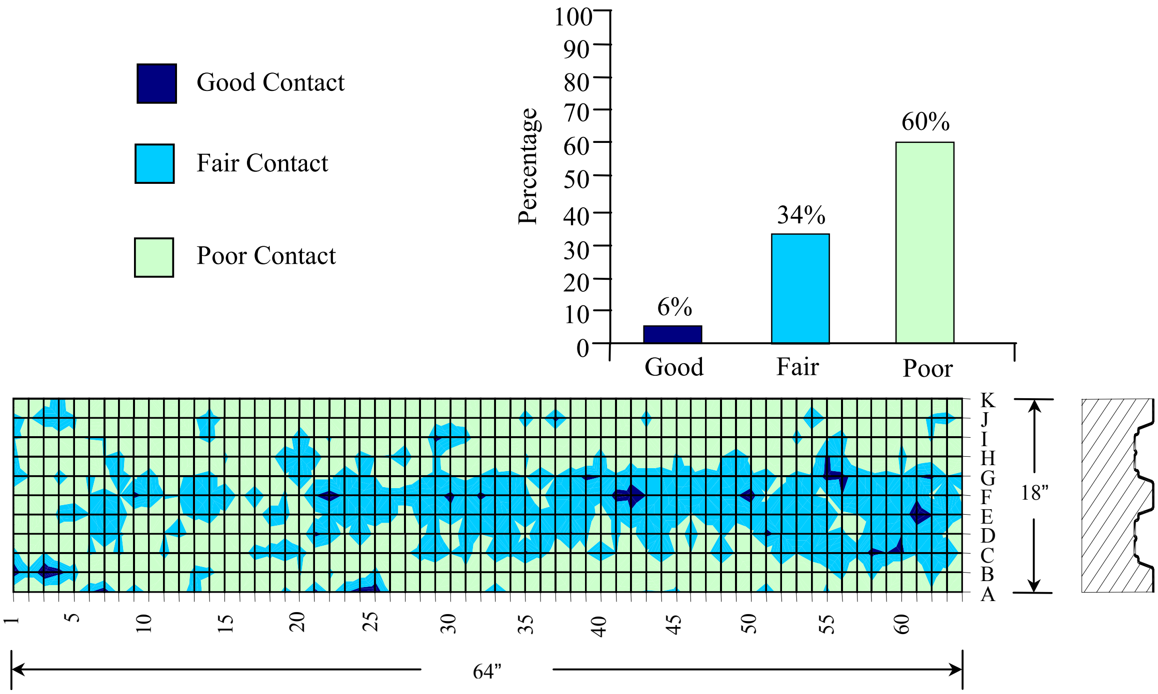


Figure 5.52. Pulse-echo contour map and bar chart
for After Cracking for specimen WI-S-10-2

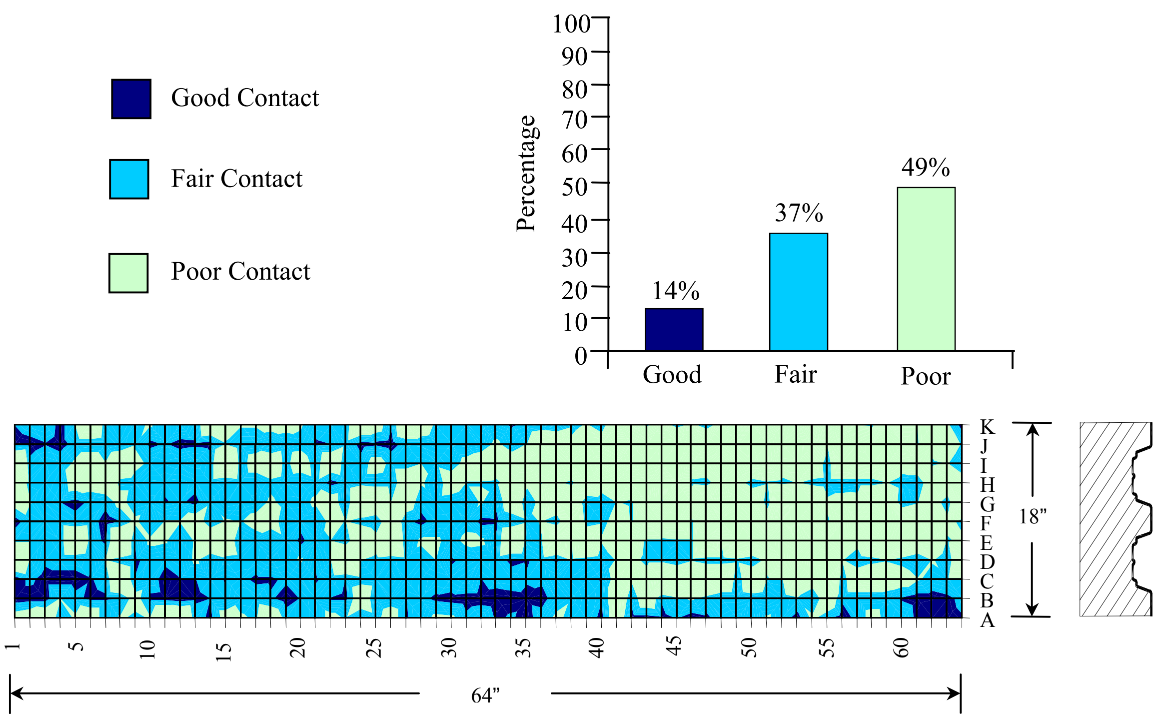


Figure 5.53. Pulse-echo contour map and bar chart
for After 1,000 hrs Salt-Water for specimen WI-S-10-2

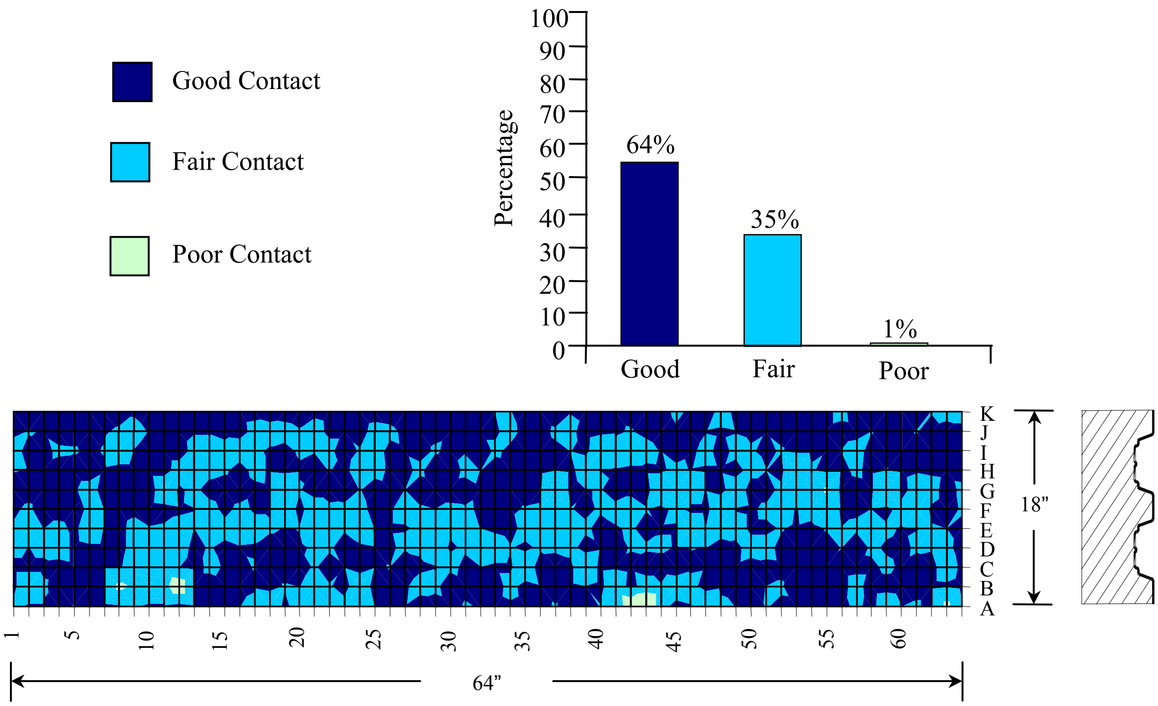


Figure 5.54. Pulse-echo contour map and bar chart
for After 3,000 hrs Salt-Water for specimen WI-S-10-2

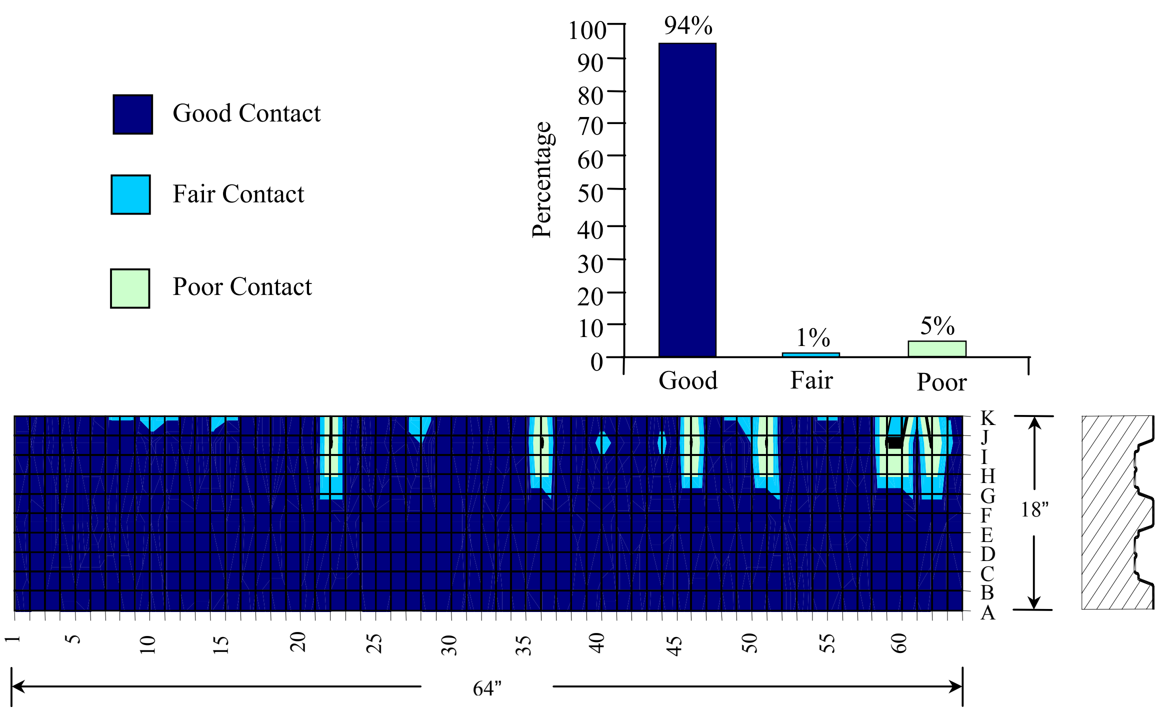


Figure 5.55. Pulse-echo contour map and bar chart
for After 10,000 hrs Salt-Water for specimen WI-S-10-2

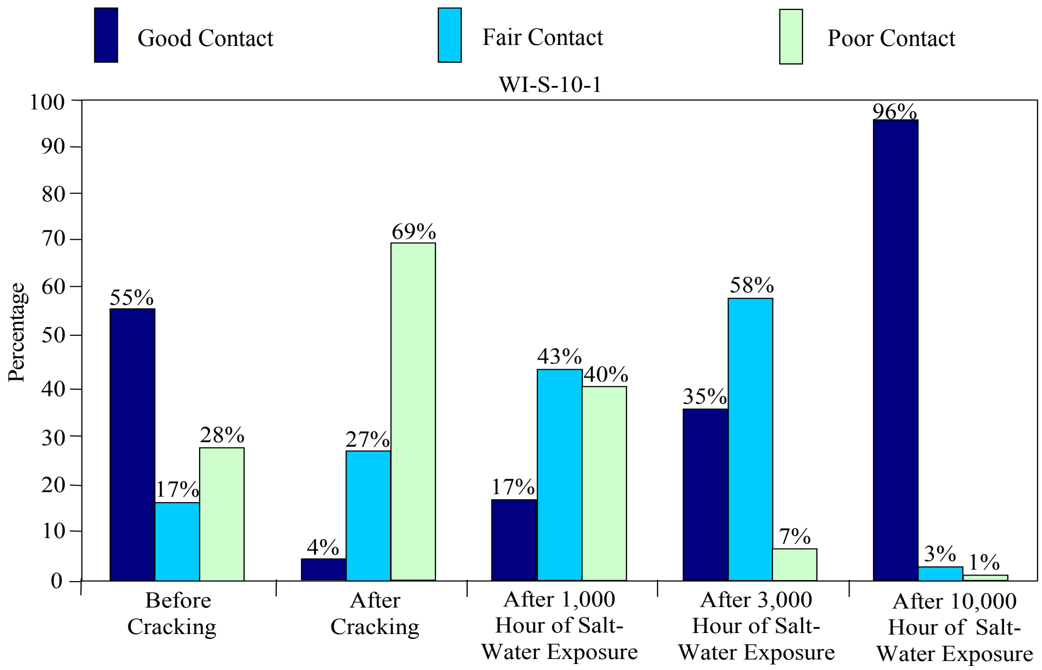


Figure 5.56. Summary of pulse-echo results for specimen WI-S-10-1

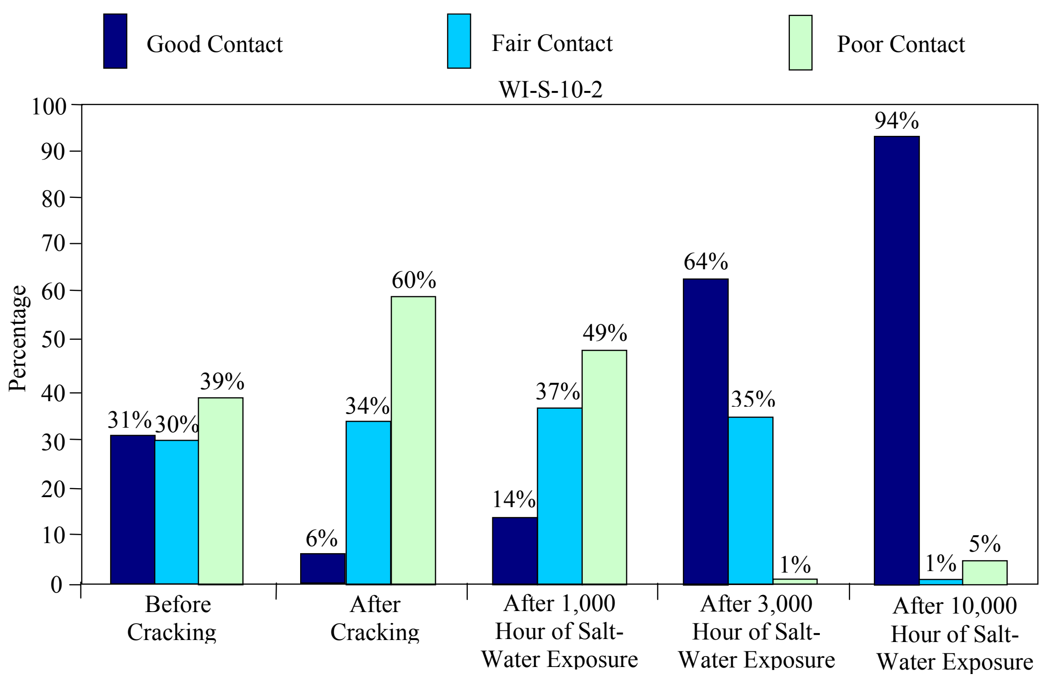


Figure 5.57. Summary of pulse-echo results for specimen WI-S-10-2

The overall trend of quality of contact between the SIPMF and the concrete is generally consistent for all salt-water exposure specimens. The initial contact (before cracking) is consistently good, a significant loss of contact occurs upon service load cracking, and an apparent improvement of contact is observed with continued salt-water exposure. The average contact ratings for all salt-water specimens before cracking were 49% good, 27% fair, and 24% poor. After cracking, the average contact ratings measured were 4% good, 21% fair, and 75% poor. After the first 1,000 hours of salt-water exposure, the average good contact rating for all specimens increased to 32%. The average good contact rating increased to 49% and 95% for 3,000 and 10,000 hours of salt-water exposure, respectively. The apparent improvement in contact is attributed to accumulation of mineral precipitate between the SIPMF and the concrete. Some similarity of spatial patterns of contact ratings are observed for the before cracking specimens. Regions of consistent contact rating appear to follow generally longitudinal trends. After cracking (and for further stages of salt-water conditioning), no distinct or consistent spatial trends are observed in the regions of consistent contact ratings.

Mineral precipitate on the salt-water exposure specimens was observed for all monitored exposure periods. SIPMFs were removed from the specimens after ultimate load tests for inspection. Some precipitate was observed on the top side of the SIPMF (side in contact with concrete) after 1,000 hours of salt-water exposure. Noticeably more precipitate was observed on the removed forms after 3,000 hours, and a similar high amount of precipitation was observed on the 10,000-hour salt-water exposures specimens. Qualitative chemical analysis conducted on precipitate collected from between the SIPMF and the concrete for 10,000-hour salt-water exposures specimens indicated presence of Calcium and Iron (traced to concrete/cement origin from lime and tetracalcium aluminoferrite), Zinc (traced to galvanized coating of SIPMF). Tests conducted on precipitate collected on the underside of the SIPMF (exposed side) on 3,000-hour salt-water exposures specimens indicated presence of Calcium, Iron, and Magnesium (traced to concrete/cement origin from i) lime, ii) tetracalcium aluminoferrite, and iii) magnesium oxide), as well as Sodium (traced to salt solution). A noteworthy observation of the analysis of the presence of precipitate is that sodium was not detected in the area between the SIPMF and the concrete.

5.3.3 Ultrasonic Through-Transmission Results

Ultrasonic through-transmission tests were conducted on a 3-in. slice removed from each specimen before ultimate load testing. Conducting through-transmission tests over a grid pattern on each slice allowed for determination of pulse-velocity over the entire longitudinal cross section of each specimen. Through-transmission test results are presented in Figures 5.58 to 5.71 for specimens with SIPMF. Results of the through-transmission tests are presented as contour maps representing various ranges of pulse-velocity. Cracks are shown as white lines in figures. The pulse velocity can be correlated to quality of concrete as presented in Chapter 4. The contour maps provide graphical representation of the spatial distribution of quality of concrete. In addition to the contour maps, these figures include profiles of average pulse velocity through the depth ($v_{ave\text{-}depth}$) and along the length ($v_{ave\text{-}longitudinal}$) of the specimens. Further interpretation of the through-transmission data is presented at the end of this chapter (chronological summaries and comparison of average pulse velocity for entire cross section, perimeter region, interior region, and bottom region of the specimens).

Control Specimens

Through-transmission test results for control specimens with SIPMF are presented in Figures 5.58 and 5.59. The average ultrasonic velocity for the entire cross sections of control specimens with SIPMF was 13,727 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for control specimens with SIPMF was 13,577 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for control specimens with SIPMF was 13,891 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for control specimens with SIPMF was 13,663 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the control specimens.

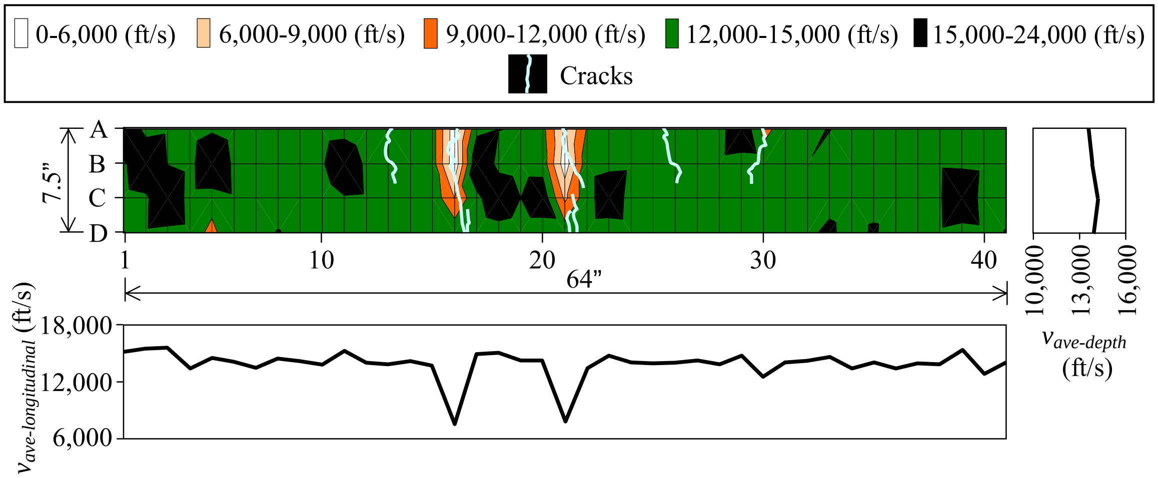


Figure 5.58. Through-transmission test results for slice from specimen WI-C-1

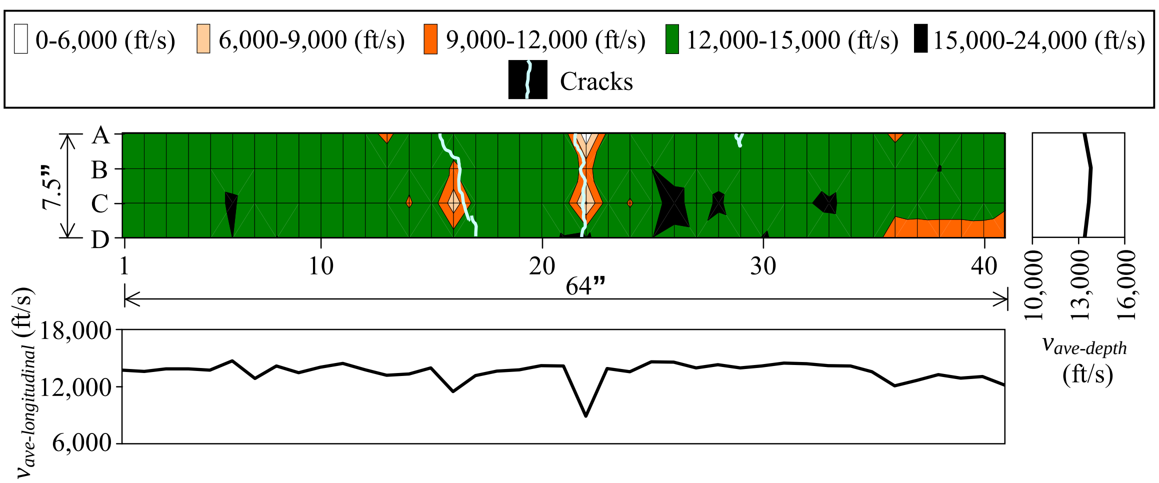


Figure 5.59. Through-transmission test results for slice from specimen WI-C-2

Freeze/Thaw Specimens

Through-transmission test results for 300-cycle freeze/thaw specimens with SIPMF are presented in Figures 5.60 and 5.61. The average ultrasonic velocity for the entire cross sections of 300-cycle freeze/thaw specimens with SIPMF was 14,525 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 300-cycle freeze/thaw specimens with SIPMF was 14,384 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 300-cycle freeze/thaw specimens with SIPMF was 14,681 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 300-cycle freeze/thaw specimens with SIPMF was 14,742 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 300-cycle freeze/thaw specimens with SIPMF.

Through-transmission test results for 600-cycle freeze/thaw specimens with SIPMF are presented in Figures 5.62 and 5.63. The average ultrasonic velocity for the entire cross sections of 600-cycle freeze/thaw specimens with SIPMF was 13,979 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 600-cycle freeze/thaw specimens with SIPMF was 13,595 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 600-cycle freeze/thaw specimens with SIPMF was 14,404 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 600-cycle freeze/thaw specimens with SIPMF was 13,412 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 600-cycle freeze/thaw specimens with SIPMF.

A summary of through-transmission test results for control specimens and freeze/thaw specimens with SIPMF is presented in Figure 5.64. The average percentages of measurement points for the control specimens with SIPMF were 2% very poor, 1% poor, 4% moderate to questionable, 84% good, and 9% very good. The average percentages of measurement points for the 300-cycle freeze/thaw specimens with SIPMF were 0% very poor, 0% poor, 1% moderate to questionable, 83% good, and 17% very good. The average percentages of measurement points for the 600-cycle freeze/thaw specimens with SIPMF were 1% very poor, 2% poor, 2% moderate to questionable, 86% good, and 9% very good.

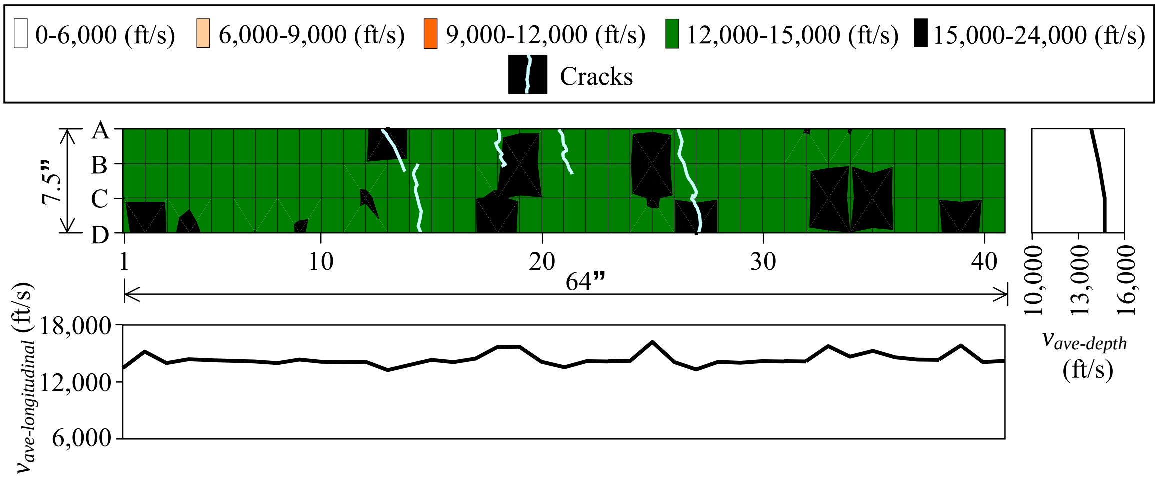


Figure 5.60. Through-transmission test results for slice from specimen WI-F-3-1

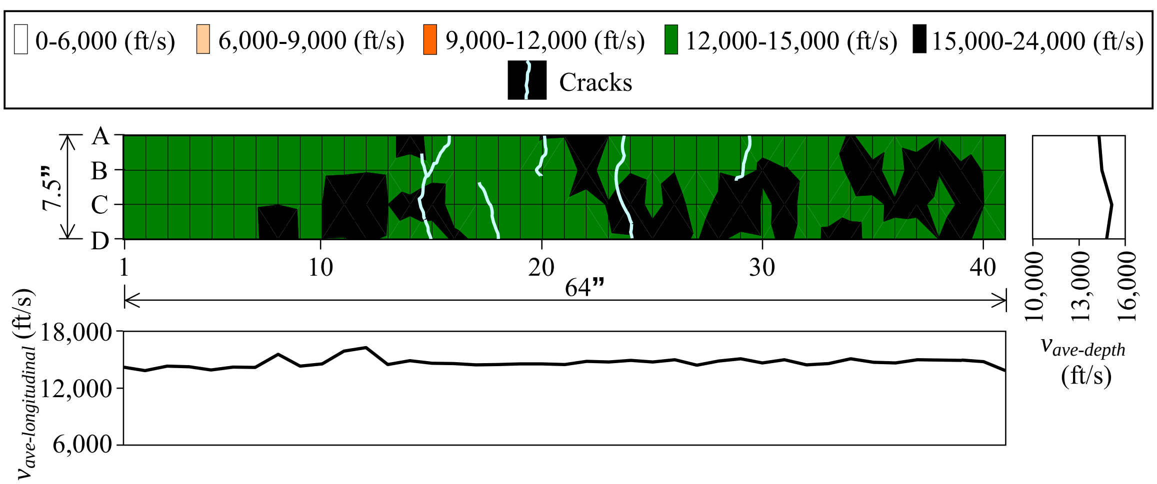


Figure 5.61. Through-transmission test results for slice from specimen WI-F-3-2

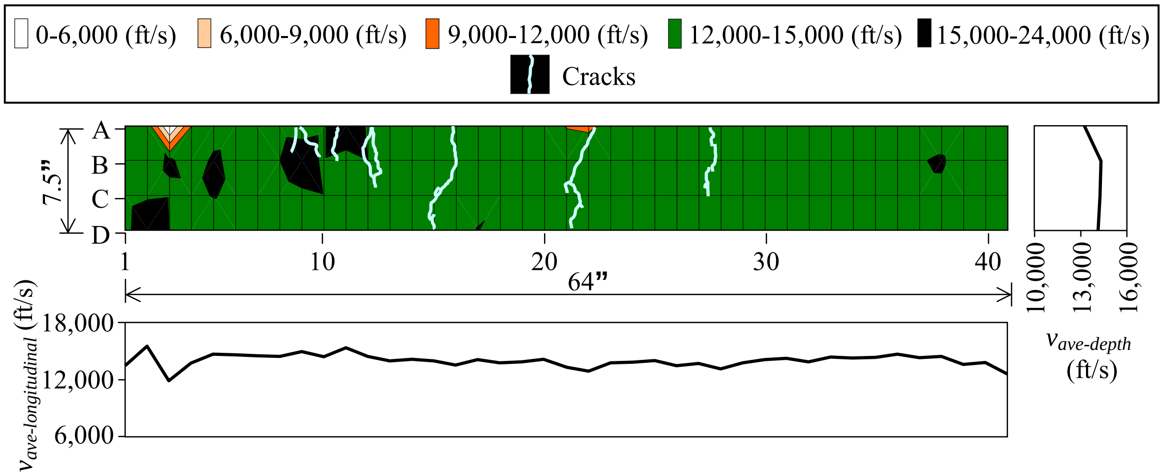


Figure 5.62. Through-transmission test results for slice from specimen WI-F-6-1

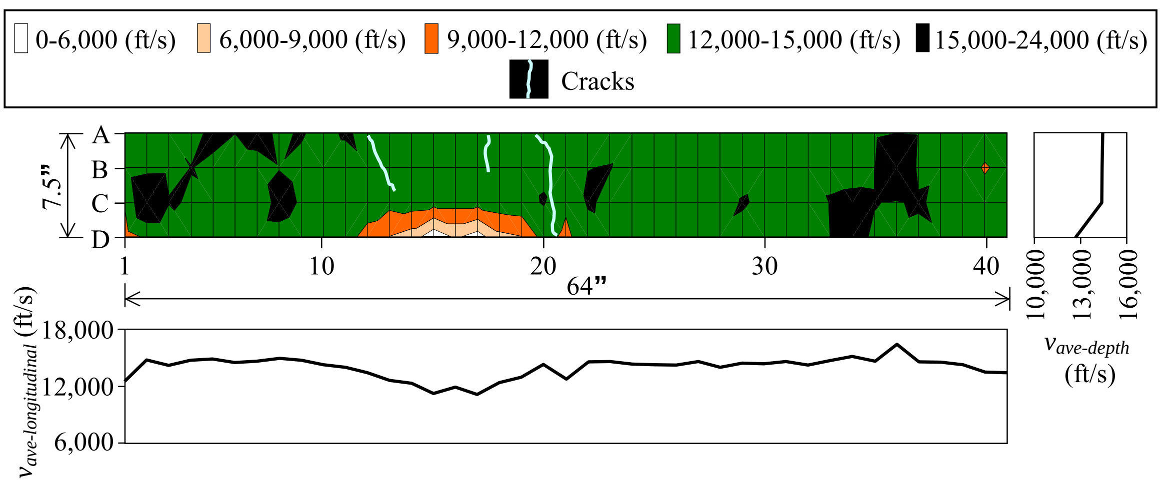


Figure 5.63. Through-transmission test results for slice from specimen WI-F-6-2

The average pulse velocity for the entire cross sections of the freeze/thaw specimens with SIPMF increased to 14,525 ft/s after 300 cycles of freeze/thaw exposure (compared to 13,727 ft/s for control specimens). A subsequent decrease in average pulse velocity to 13,979 ft/s was measured for the 600 cycle specimens, although the average pulse velocity after 600 cycles was still greater than that for the control specimens. The overall increase in pulse velocity after freeze/thaw exposure is attributed to improved hydration conditions in the presence of frequent wetting of the specimens.

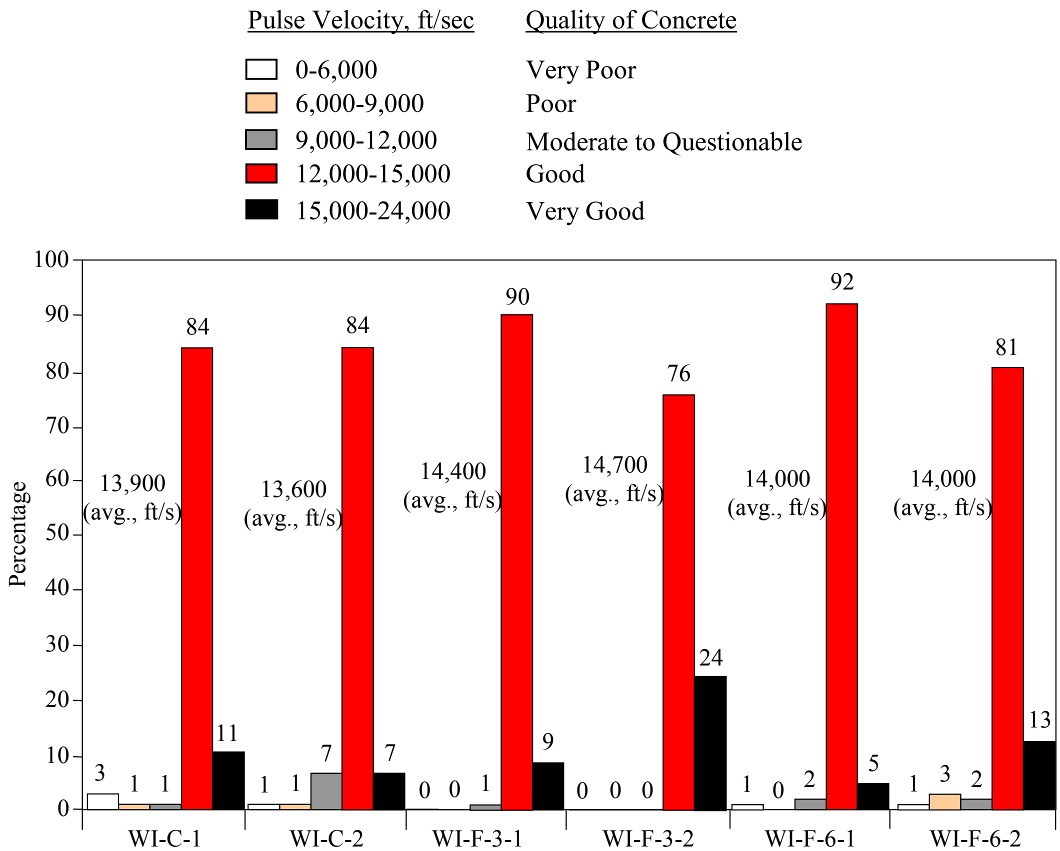


Figure 5.64. Summary of through-transmission test results for control and freeze/thaw exposure specimens with SIPMF

Salt-Water Specimens

Through-transmission test results for 1,000-hour salt-water exposures specimens with SIPMF are presented in Figures 5.65 and 5.66. The average ultrasonic velocity for the entire cross sections of 1,000-hour salt-water exposures specimens with SIPMF was 13,575 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 1,000-hour salt-water exposures specimens with SIPMF was 13,487 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 1,000-hour salt-water exposures specimens with SIPMF was 13,673 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 1,000-hour salt-water exposures specimens with SIPMF was 13,275 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 1,000-hour salt-water exposures specimens with SIPMF.

Through-transmission test results for 3,000-hour salt-water exposures specimens with SIPMF are presented in Figures 5.67 and 5.68. The average ultrasonic velocity for the entire cross sections of 3,000-hour salt-water exposures specimens with SIPMF was 14,056 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 3,000-hour salt-water exposures specimens with SIPMF was 14,081 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 3,000-hour salt-water exposures specimens with SIPMF was 14,029 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 3,000-hour salt-water exposures specimens with SIPMF was 13,876 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 3,000-hour salt-water exposures specimens with SIPMF.

Through-transmission test results for 10,000-hour salt-water exposures specimens with SIPMF are presented in Figures 5.69 and 5.70. The average ultrasonic velocity for the entire cross sections of 10,000-hour salt-water exposures specimens with SIPMF was 15,025 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 10,000-hour salt-water exposures specimens with SIPMF was 14,987ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 10,000-hour salt-water exposures specimens with SIPMF was 15,067ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 10,000-hour salt-water exposures specimens with SIPMF was 15,198 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 10,000-hour salt-water exposures specimens with SIPMF.

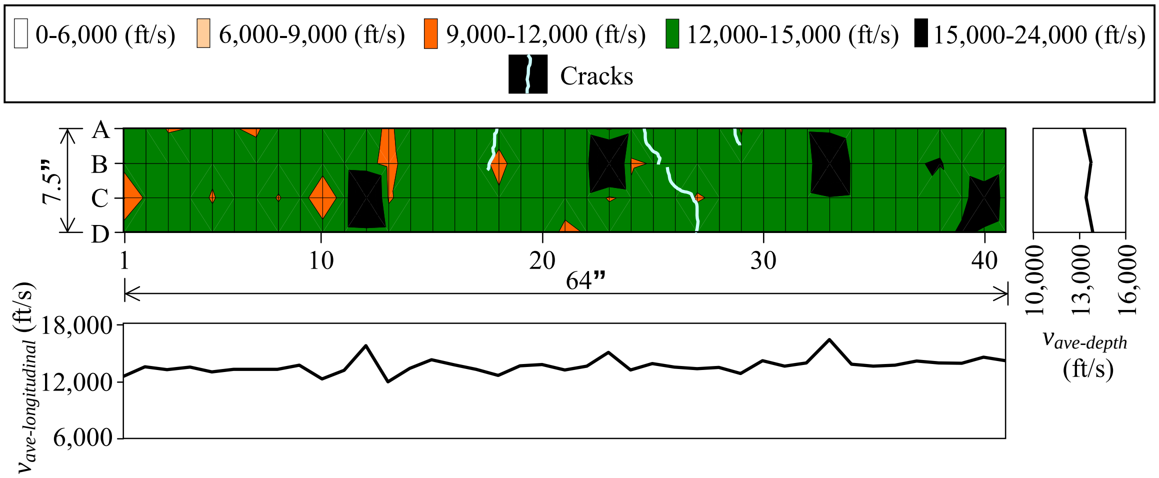


Figure 5.65. Through-transmission test results for slice from specimen WI-S-1-1

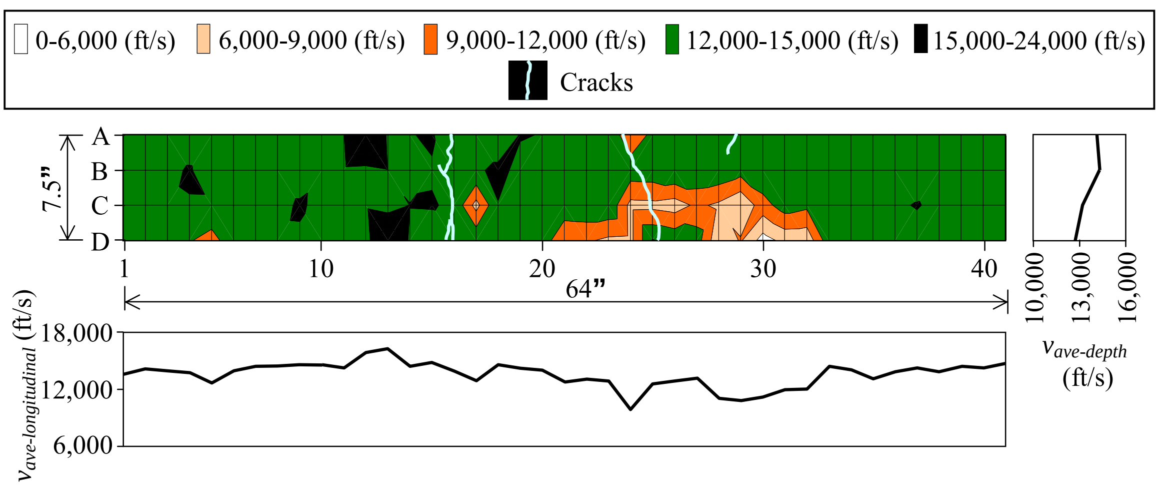


Figure 5.66. Through-transmission test results for slice from specimen WI-S-1-2

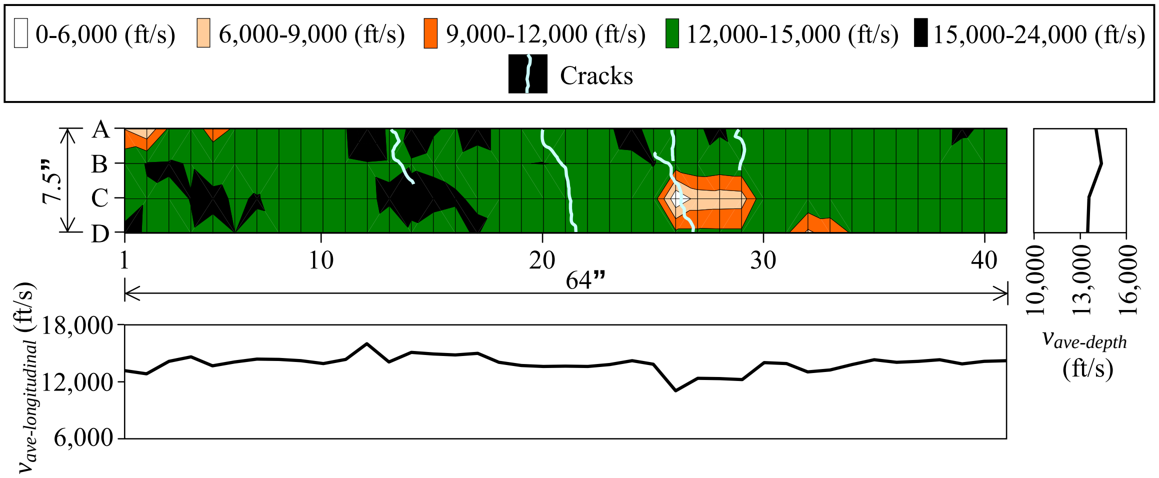


Figure 5.67. Through-transmission test results for slice from specimen WI-S-3-1

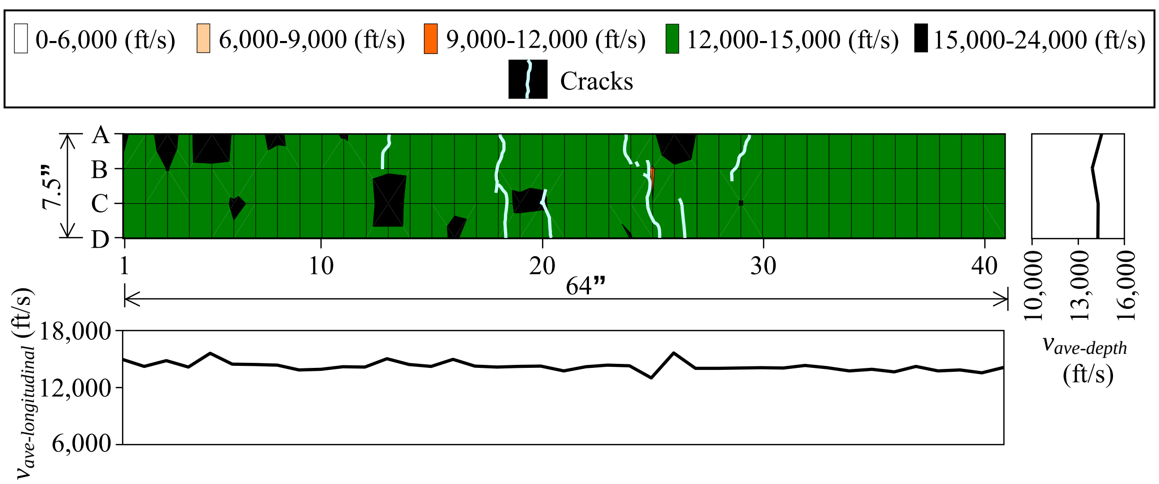


Figure 5.68. Through-transmission test results for slice from specimen WI-S-3-2

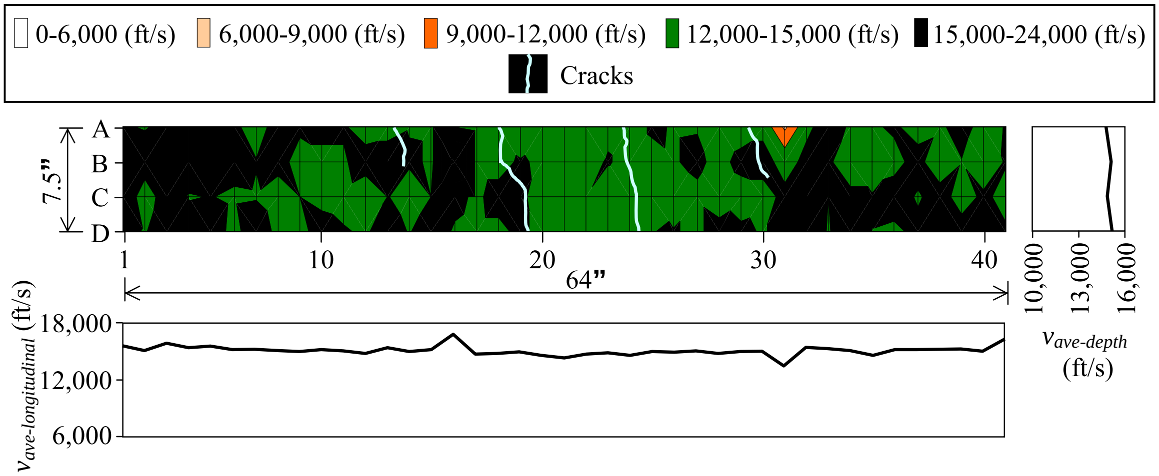


Figure 5.69. Through-transmission test results for slice from specimen WI-S-10-1

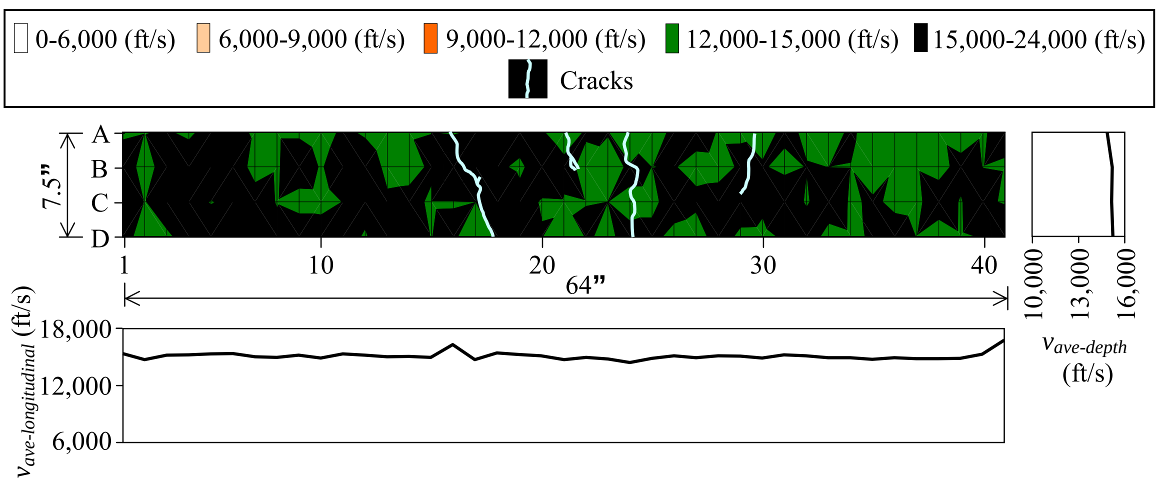


Figure 5.70. Through-transmission test results for slice from specimen WI-S-10-2

A summary of through-transmission test results for control specimens and salt-water specimens with SIPMF is presented in Figure 5.71. The average percentages of measurement points for the control specimens with SIPMF were 2% very poor, 1% poor, 4% moderate to questionable, 84% good, and 9% very good. The average percentages of measurement points for the 1,000-hour salt-water exposures specimens with SIPMF were 0% very poor, 4% poor, 7% moderate to questionable, 84% good, and 5% very good. The average percentages of measurement points for the 3,000-hour salt-water exposures specimens with SIPMF were 0%

very poor, 2% poor, 1% moderate to questionable, 86% good, and 11% very good. The average percentages of measurement points for the 10,000-hour salt-water exposures specimens with SIPMF were 0% very poor, 1% poor, 0% moderate to questionable, 54% good, and 46% very good.

The average pulse velocity for the entire cross sections of the 1,000-hour salt-water specimens (13,575 ft/s) was similar to the control specimens (13,727 ft/s). The average pulse velocity for the entire cross sections increased monotonically with further salt-water exposure (14,056 ft/s for the 3,000-hour salt-water specimens and 15,025 ft/s for the 10,000-hour salt-water specimens). The consistent increase in pulse velocity after salt-water exposure is attributed to improved hydration conditions for specimens submerged in a tank.

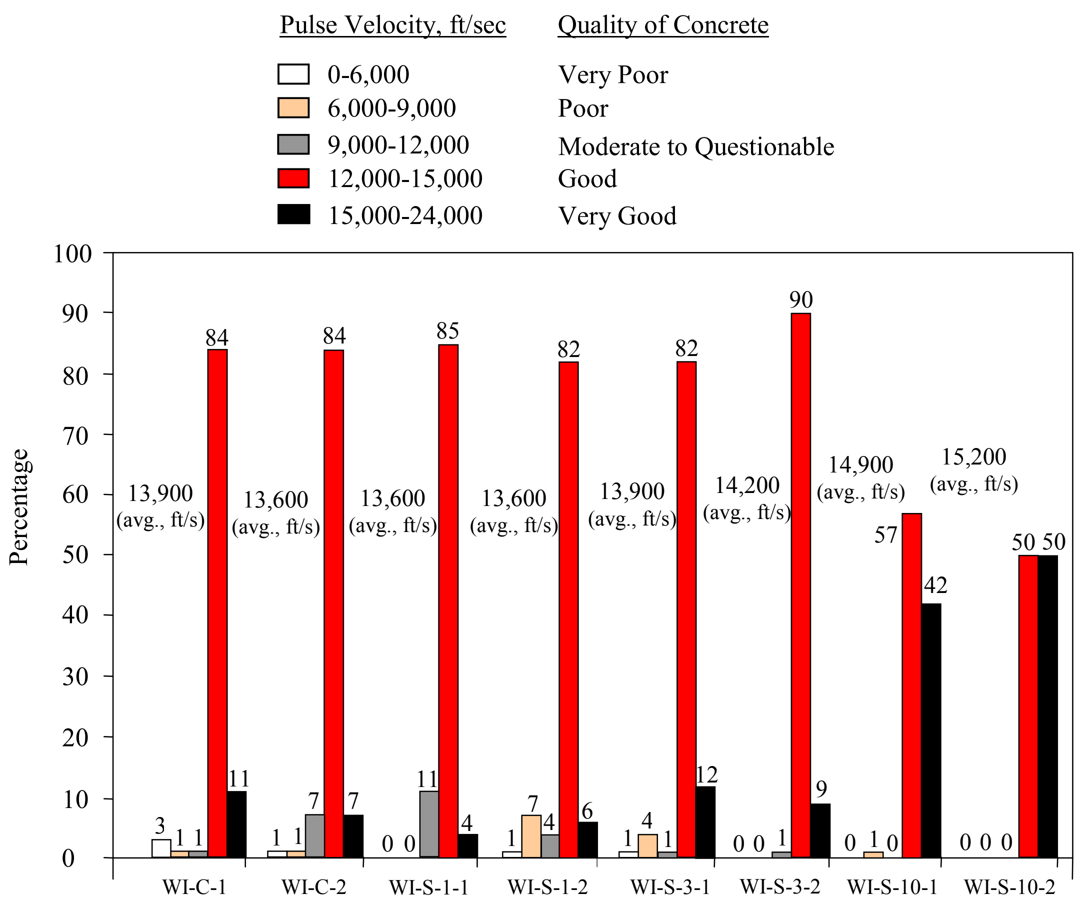


Figure 5.71. Summary of through-transmission test results for control and salt-water exposure specimens with SIPMF

5.3.4 Ultimate Load Test Results

Ultimate load test was applied on each specimen at the end of the environmental exposures, and the load setup "TW" was used for ultimate load tests. Ultimate load test results are presented for control specimens, freeze/thaw specimens, and salt-water specimens with SIPMF in this section. For ultimate load tests on specimens with SIPMF, failure modes observed were flexural, shear, and flexural/shear (Figure 5.72).

a. Flexural failure mode

b. Shear failure mode

c. Flexural/shear failure mode

Figure 5.72. Mode of failures for specimens with SIPMF

Control Specimens

The ultimate load tests were conducted for control specimens with SIPMF after 287 days of curing (WI-C-1) and 568 days of curing (WI-C-2). The failure mode for both control specimens was a shear failure mode. The ulitmate load was 33.25 kips and the deflection corresponding to peak load was 0.49 in. for WI-C-1. The ultimate load was 36.71 kips, and the deflection corresponding to peak load was 0.60 in. for WI-C-2. Graphical and tabular summaries of the control specimen results are presented in comparison to the environmental exposure tests in the following sections.

Additional strength was achieved over the extended curing period for WI-C-2. The ultimate load of control specimens was estimated using either the strength design method for flexural capacity or the shear strength calculation for shear capacity and the results from corresponding compressive strength (cylinder) tests. The predicted strengths for the control specimens were 33.32 kips/ 34.67 kips (flexural/shear) for WI-C-1 and 33.79 kips/ 34.02 kips (flexural/shear) for WI-C-2, respectively. Generally, good agreement is observed between predicted and experimental results.

Results from the control specimens were used as baseline values for comparison to the specimens that were subjected to environmental exposure. Ultimate load tests were conducted on the control specimens on dates that coincided with tests for the shortest environmental exposure conditions (1,000 hour salt-water exposure) and for the longest environmental exposure conditions (10,000 hour salt-water exposure) to account for expected changes in baseline strength with time due to curing. Linear interpolation was applied to data from the control specimens to estimate baseline values for comparative tests conducted at intermediate stages (300 and 600 freeze/thaw cycle and 3,000 hour salt-water specimens) [Figure 5.73].

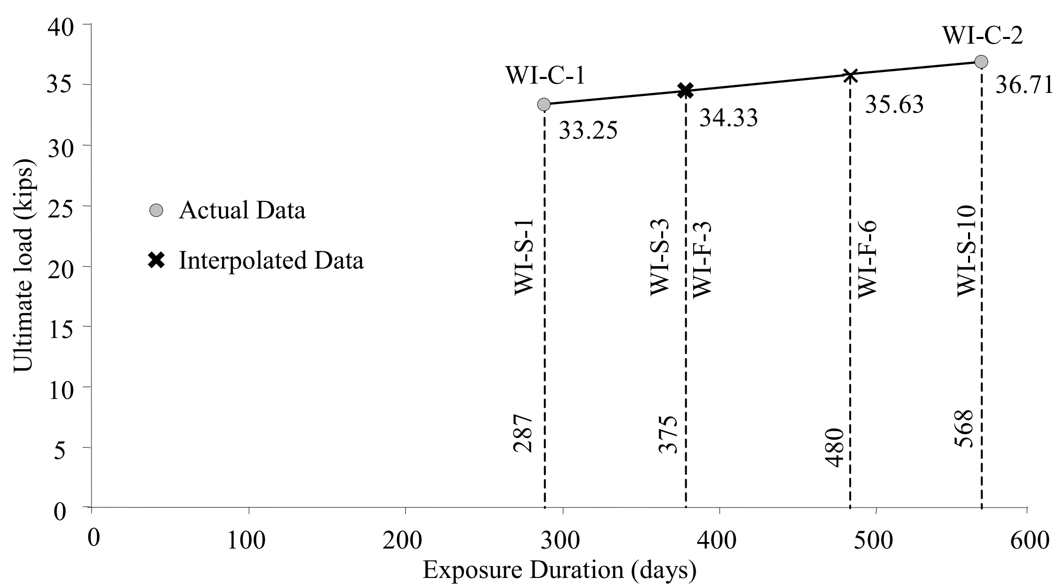


Figure 5.73. Interpolation of control values for freeze/thaw and salt-water specimens with SIPMF

Freeze/Thaw Specimens

The ultimate load tests were conducted for Freeze/Thaw specimens with SIPMF after 375 days of curing (300 cycles) and 480 days of curing (600 cycles). The failure mode for all freeze/thaw specimens was flexural failure mode with the exception of WI-F-6-1, which failed in flexural/shear failure mode. For WI-F-3-1, the ultimate load was 31.52 kips and the deflection corresponding to peak load was 0.82 in. For WI-F-3-2, the ultimate load was 33.05 kips and the deflection corresponding to peak load was 0.75 in. For WI-F-6-1, the ultimate load was 34.64 kips and the deflection corresponding to peak load was 0.73 in. For WI-F-6-2, the ultimate load was 32.78 kips and the deflection corresponding to peak load was 0.52 in. A graph containing all ultimate load test results for freeze/thaw and control specimens with SIPMFs is presented in Figure 5.74. A summary of results is presented in Table 5.3.

A comparison was made to determine the effect of freeze/thaw exposure on ultimate load of specimens with SIPMF (Figure 5.75). Appropriate baseline values for comparison were determined from control specimens. A reduction in ultimate load as compared to baseline values was observed for all freeze/thaw specimens with SIPMFs. After 300 cycles of freeze/thaw exposure, reductions in ultimate load as compared to baseline values were 8.2% and 3.7% for an average reduction of 5.9%. After 600 cycles of freeze/thaw exposure, reductions in ultimate load as compared to baseline values were 8.0% and 2.8% for an average reduction of 5.4%. These data indicate that deterioration of specimens occurs due to freeze/thaw exposure. Minimal difference is observed between 300 and 600 freeze/thaw cycles.

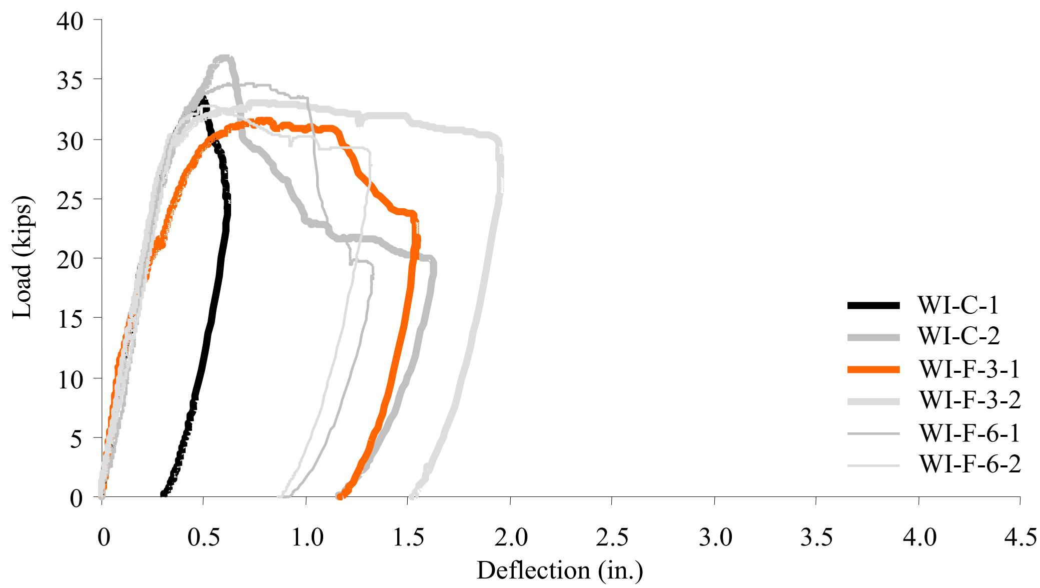


Figure 5.74. Load-deflection curves for ultimate load of control and freeze/thaw exposure specimens with SIPMF

Table 5.3. Ultimate load results for control and freeze/thaw exposure specimens with SIPMF

Specimen	**Mode of Failure**	**Failure Load** (kips)		**Baseline Value** (kips)	**Deflection at Ultimate Load** (in.)	**Percentage of Change in Deflection**		**Percentage of Change in Capacity**	
WI-C-1	Shear	33.25	(--)	(--)	0.49	(--)		(--)	
WI-C-2	Shear	36.71			0.60				
WI-F-3-1	Flexural	31.52	Average 32.29	34.33[a]	0.82	56.5%	Average 49.8%	- 8.2%	Average - 5.9%
WI-F-3-2	Flexural	33.05			0.75	43.1%		- 3.7%	
WI-F-6-1	Flexural/ Shear	34.64	Average 33.71	35.63[a]	0.73	29.0%	Average 10.5%	- 2.8%	Average - 5.4%
WI-F-6-2	Flexural	32.78			0.52	-8.1%		- 8.0%	

[a] Linear interpolation used between control specimens to estimate baseline value

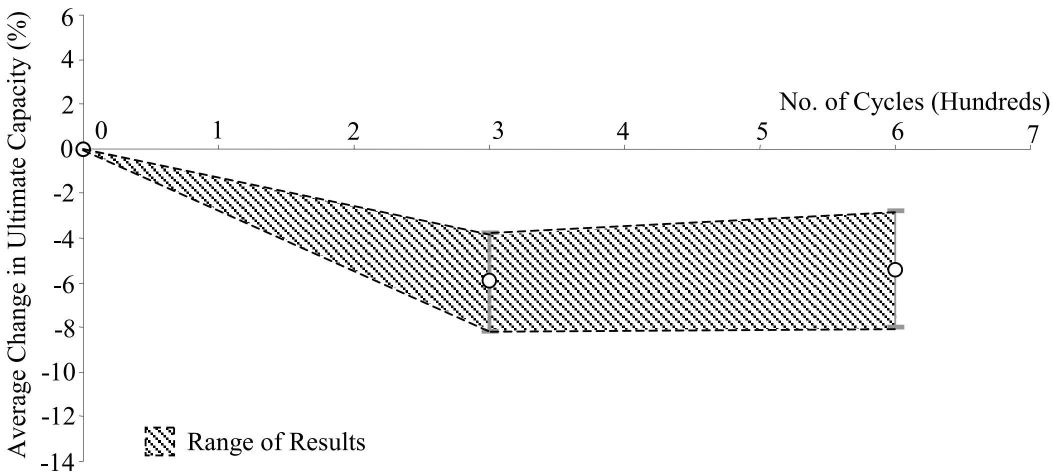


Figure 5.75. Percentage of change in ultimate load carrying capacity for freeze/thaw exposure specimens with SIPMF

Salt-Water Specimens

The ultimate load tests were conducted for Salt-Water specimens with SIPMF after 287 days of curing (1,000 hour specimens), 375 days of curing (3,000 hour specimens) and 586 days of curing (10,000 hour specimens). The failure mode for all salt-water specimens was flexural failure mode with the exception of WI-S-10-1, which failed in shear failure mode. For WI-S-1-1, the ultimate load was 33.35 kips and the deflection corresponding to peak load was 0.53 in. For WI-S-1-2, the ultimate load was 35.81 kips and the deflection corresponding to peak load was 0.54 in. For WI-S-3-1, the ultimate load was 32.80 kips and the deflection corresponding to peak load was 0.70 in. For WI-S-3-2, the ultimate load was 32.56 kips and the deflection corresponding to peak load was 0.82 in. For WI-S-10-1, the ultimate load was 35.13 kips and the deflection corresponding to peak load was 0.71 in. For WI-S-10-2, the ultimate load was 32.70 kips and the deflection corresponding to peak load was 0.73 in. A graph containing all ultimate load test results for salt-water and control specimens with SIPMFs is presented in Figure 5.76. A summary of results is presented in Table 5.4.

A comparison was made to determine the effect of salt-water exposure on ultimate load of specimens with SIPMF (Figure 5.77). Appropriate baseline values for comparison were determined from control specimens. An initial increase in ultimate load is observed after 1,000 hours of salt-water exposure as compared to baseline values followed by a decrease in ultimate load due to further salt-water exposure. After 1,000 hours of salt-water exposure, increases in ultimate load as compared to baseline values were 0.3% and 7.7% for an average increase of 4.0%. After 3,000 hours of salt-water exposure, reductions in ultimate load as compared to baseline values were 4.5% and 5.2% for an average reduction of 4.8%. After 10,000 hours of salt-water exposure, further reductions in ultimate load as compared to baseline values were observed as 4.3% and 10.9% for an average reduction of 7.6%. These data indicate that structural deterioration of specimens occurs due to salt-water exposure. The observed reduction in ultimate load was most prominent between specimens exposed to 1,000 and 3,000 hours of salt-water.

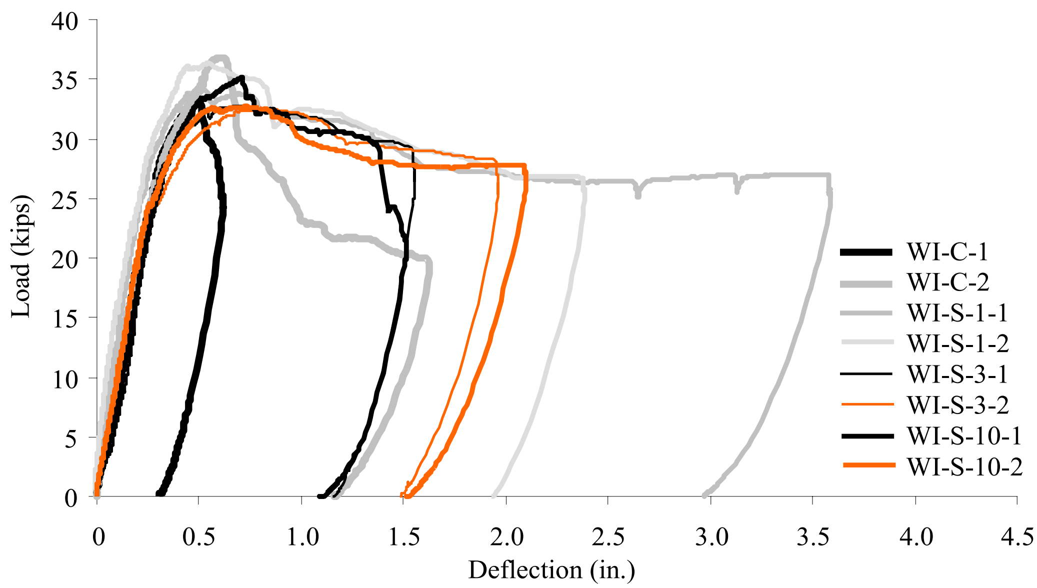


Figure 5.76. Load-deflection curves for ultimate load of 1,000-, 3,000-, 10,000-hour salt-water exposures, and control specimens with SIPMF

Table 5.4. Ultimate load results for 1,000-, 3,000-, 10,000-hour salt-water exposures, and control specimens with SIPMF

Specimen	Mode of Failure	Failure Load (kips)		Baseline Value (kips)	Deflection at Ultimate Load (in.)	Percentage of Change in Deflection		Percentage of Change in Capacity	
WI-C-1	Shear	33.25	(--)	(--)	0.49	(--)		(--)	
WI-C-2	Shear	36.71			0.60				
WI-S-1-1	Flexural	33.35	Average 34.58	33.25	0.53	8.2%	Average 9.2%	+ 0.3%	Average + 4.0%
WI-S-1-2	Flexural	35.81			0.54	10.2%		+ 7.7%	
WI-S-3-1	Flexural	32.80	Average 32.68	34.33[a]	0.70	33.6%	Average 45.1%	- 4.5%	Average - 4.8%
WI-S-3-2	Flexural	32.56			0.82	56.5%		- 5.2%	
WI-S-10-1	Shear	35.13	Average 33.92	36.71	0.71	18.3%	Average 20.0%	- 4.3%	Average - 7.6%
WI-S-10-2	Flexural	32.70			0.73	21.7%		- 10.9%	

[a] Linear interpolation used between control specimens to estimate baseline value

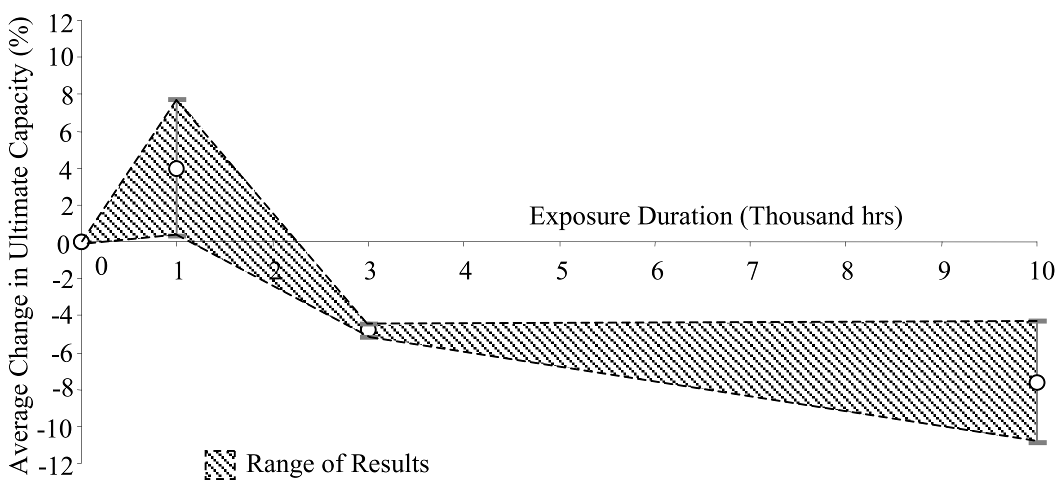


Figure 5.77. Percentage of change in ultimate load carrying capacity for salt-water exposure specimens with SIPMF

5.4 SPECIMENS WITHOUT SIPMF

Results of exposure and load tests for specimens without SIPMFs are presented in this section. First, results from the service load tests are presented. Next, ultrasonic through-transmission test results are presented to provide assessment of the quality of concrete over the longitudinal cross sections of all specimens following exposure tests. Finally, ultimate load test results are presented to evaluate the influence of various exposure conditions on the ultimate load capacity of the specimens.

5.4.1 Service Load Test Results

All 12 specimens without SIPMF were subjected to a service load test at the beginning of the test program to promote full depth cracks. The service load test consisted of two steps: positive moment (bottom cracking) and negative moment (top cracking) applications. The load-displacement curves for the service load tests for specimens without SIPMF are presented in Figures 5.78 and 5.79. The bottom and top cracking loads for specimens without SIPMF are presented in Table 5.5. The onset of cracking for the positive moment application for specimens without SIPMF occurred at loads between 6.23 kips to 7.59 kips. The onset of cracking for the negative moment application occurred at loads between 3.15 kips to 5.17 kips. The range of loads associated with onset of cracking is shown as a shaded envelope on Figures 5.78 and 5.79. The theoretical cracking load was determined for specimens without SIPMF using the elastic theory with the compressive strength f_c' data from the 28-day compressive strength test cylinders. The measured loads for positive moment cracking were generally consistent with theoretical calculations of cracking loads. The theoretical prediction was 8.81 kips, which was within 27% of the average measured value for all specimens (6.90 kips). The measured loads for negative moment cracking were lower than theoretical predictions. The difference in measured and predicted values was attributed to the weakened overall structure due to presence of positive moment cracks at the time of negative moment application. The average measured value for all specimens was 4.17 kips, whereas the theoretical predicted ultimate load was 8.81 kips.

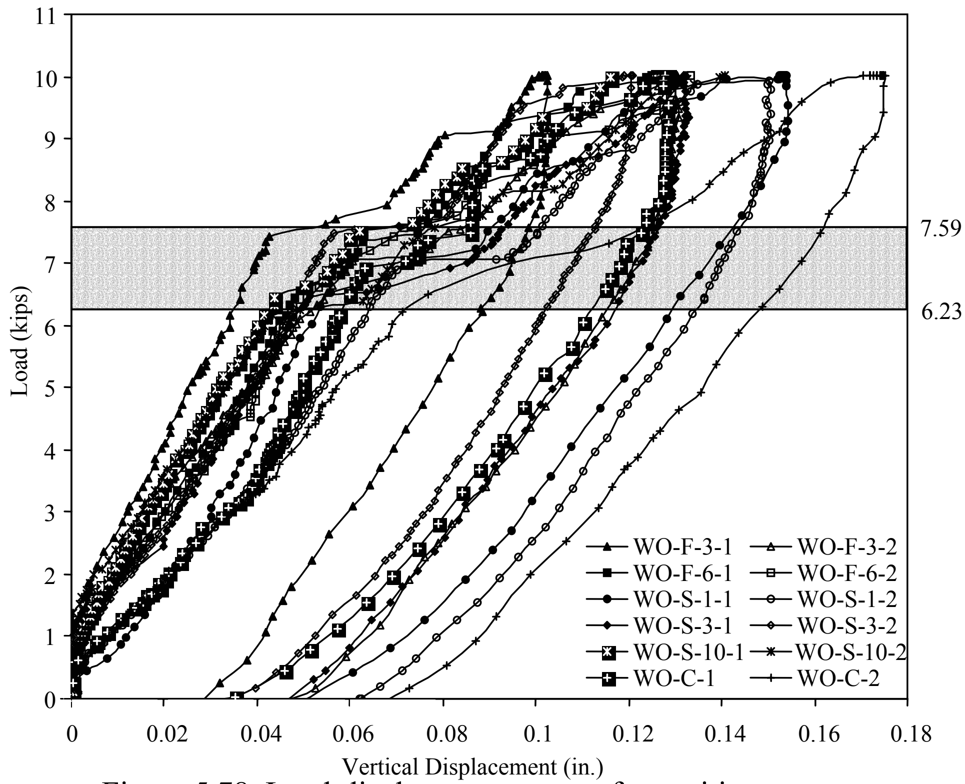


Figure 5.78. Load-displacement curves for positive moment application (bottom cracking) for specimens without SIPMF

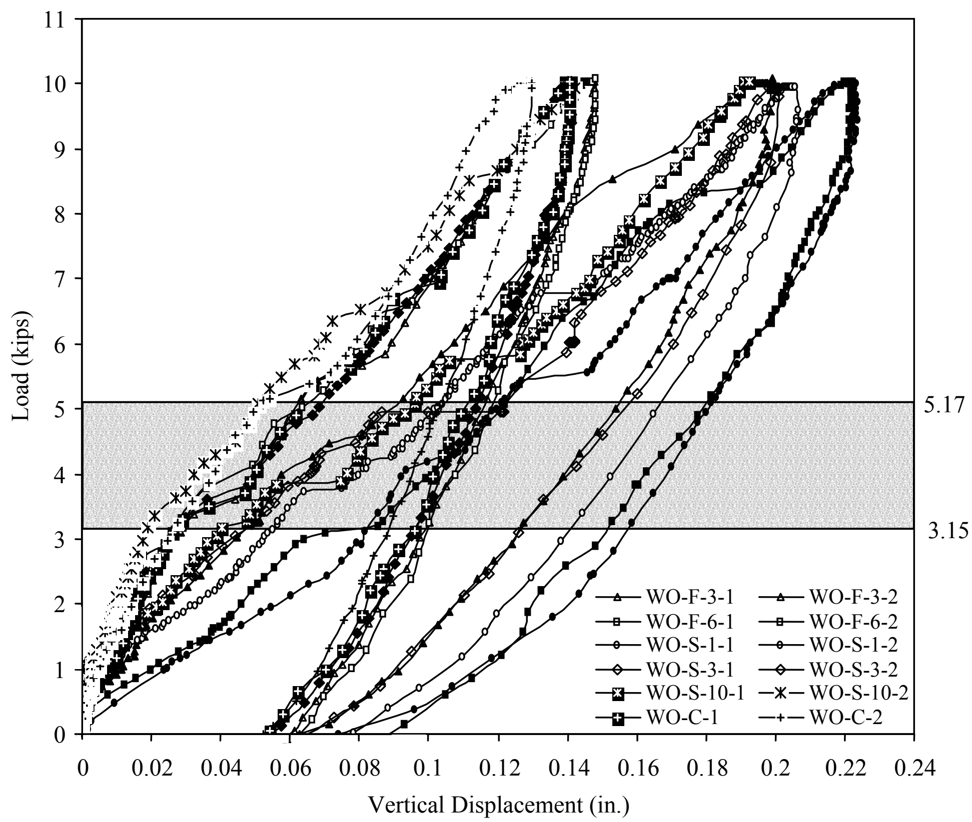


Figure 5.79. Load-displacement curves for negative moment application (top cracking) for specimens without SIPMF

Table 5.5. Top and bottom cracking load for the specimens without SIPMF

Type of specimens				Cracking Load (kips)	
				Top Cracking	**Bottom Cracking**
Specimens without SIPMF	**Control**		WO-C-1	3.45	6.97
			WO-C-2	5.17	6.59
	Freeze/Thaw	**300 cycle**	WO-F-3-1	3.25	7.59
			WO-F-3-2	3.59	7.06
		600 cycle	WO-F-6-1	3.15	6.74
			WO-F-6-2	3.82	6.43
	Salt-Water	**1,000 hr**	WO-S-1-1	4.12	6.73
			WO-S-1-2	3.74	7.02
		3,000 hr	WO-S-3-1	3.64	6.51
			WO-S-3-2	4.46	7.54
		10,000 hr	WO-S-10-1	3.21	6.61
			WO-S-10-2	3.42	6.23

5.4.2 Ultrasonic Through-Transmission Results

Ultrasonic through-transmission tests were conducted on a 3-in. slice removed from each specimen before ultimate load testing. Conducting through-transmission tests over a grid pattern on each slice allowed for determination of pulse-velocity over the entire longitudinal cross section of each specimen. Through-transmission test results are presented in Figures 5.80 to 5.93 for specimens without SIPMF. Results of the through-transmission tests are presented as contour maps representing various ranges of pulse-velocity. The pulse velocity can be correlated to quality of concrete as presented in Chapter 4. The contour maps provide graphical representation of the spatial distribution of quality of concrete. In addition to the contour maps, these figures include profiles of average pulse velocity through the depth ($v_{ave\text{-}depth}$) and along the length ($v_{ave\text{-}longitudinal}$) of the specimens. Further interpretation of the through-transmission data is presented at the end of this chapter (chronological summaries and comparison of average pulse velocity for entire cross section, perimeter region, interior region, and bottom region of the specimens).

Control Specimens

Through-transmission test results for control specimens without SIPMF are presented in Figures 5.80 and 5.81. The average ultrasonic velocity for the entire cross sections of control specimens without SIPMF was 13,244 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for control specimens without SIPMF was 12,894 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for control specimens without SIPMF was 13,691 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for control specimens without SIPMF was 12,535 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the control specimens.

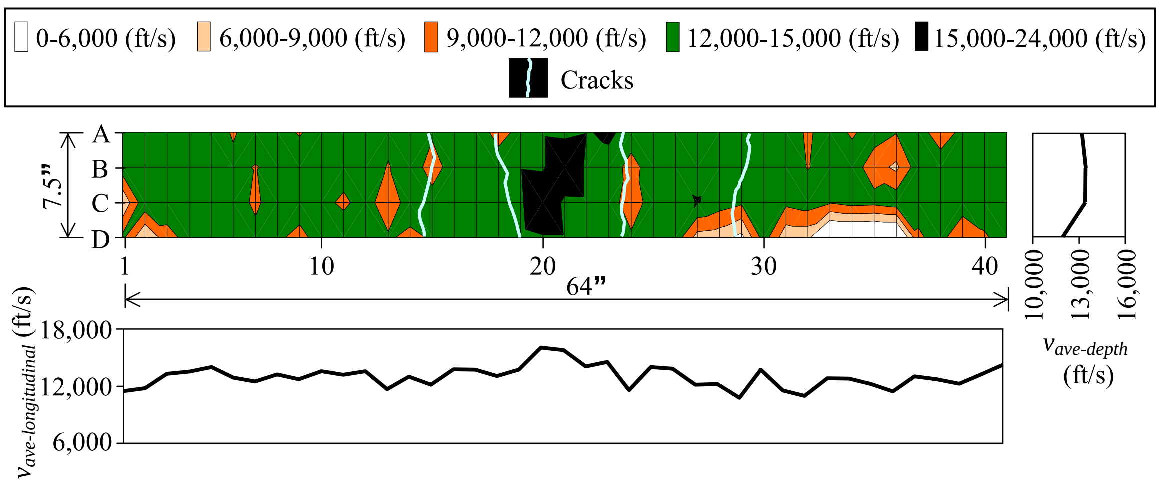


Figure 5.80. Through-transmission test results for slice from specimen WO-C-1

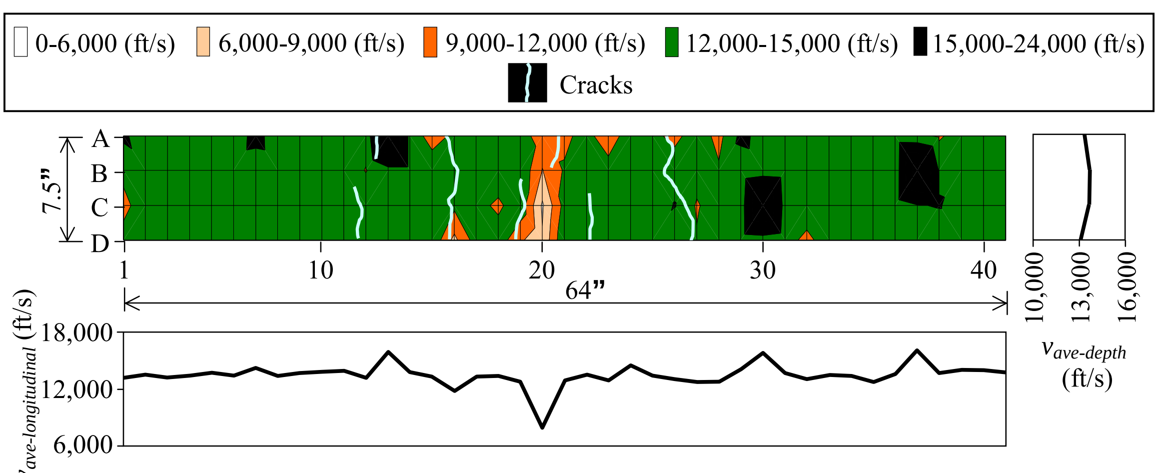


Figure 5.81. Through-transmission test results for slice from specimen WO-C-2

Freeze/Thaw Specimens

Through-transmission test results for 300-cycle freeze/thaw specimens without SIPMF are presented in Figures 5.82 and 5.83. The average ultrasonic velocity for the entire cross sections of 300-cycle freeze/thaw specimens without SIPMF was 13,360 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 300-cycle freeze/thaw specimens without SIPMF was 13,279 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 300-cycle freeze/thaw specimens without SIPMF was 13,449 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 300-cycle freeze/thaw specimens without SIPMF was 13,449 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 300-cycle freeze/thaw specimens without SIPMF.

Through-transmission test results for 600-cycle freeze/thaw specimens without SIPMF are presented in Figures 5.84 and 5.85. The average ultrasonic velocity for the entire cross sections of 600-cycle freeze/thaw specimens without SIPMF was 14,457 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 600-cycle freeze/thaw specimens without SIPMF was 14,324 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 600-cycle freeze/thaw specimens without SIPMF was 14,600 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 600-cycle freeze/thaw specimens without SIPMF was 14,575 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 600-cycle freeze/thaw specimens without SIPMF.

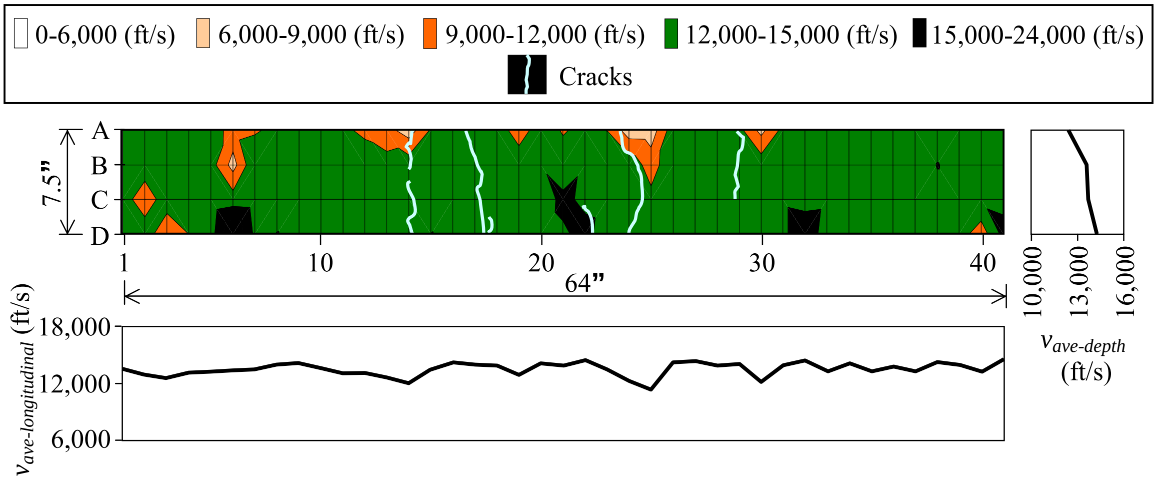


Figure 5.82. Through-transmission test results for slice from specimen WO-F-3-1

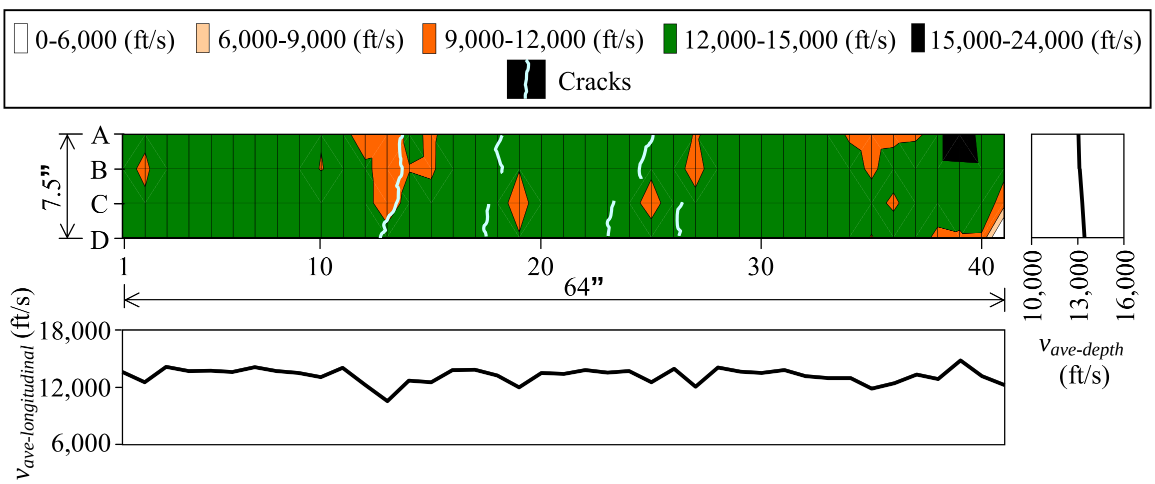


Figure 5.83. Through-transmission test results for slice from specimen WO-F-3-2

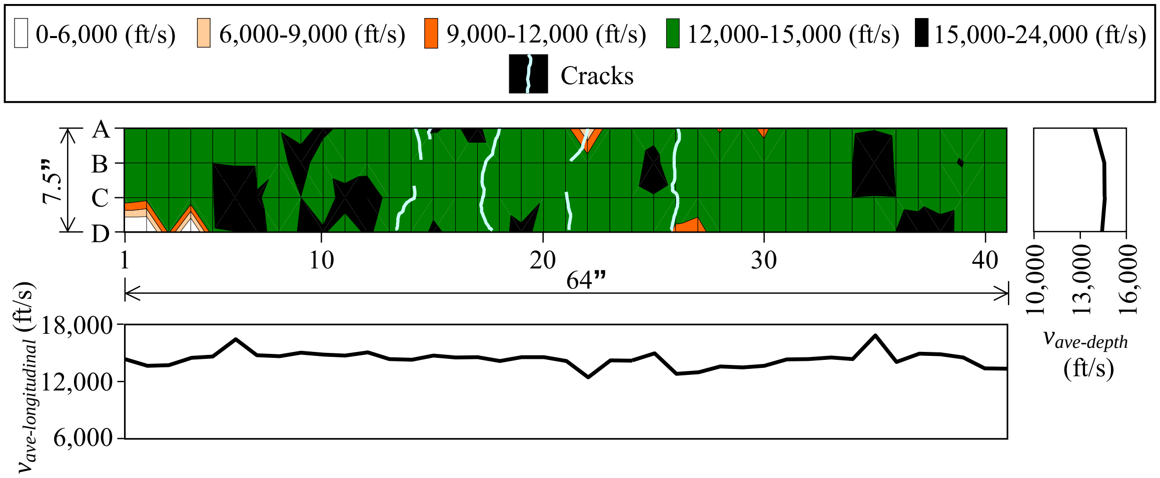


Figure 5.84. Through-transmission test results for slice from specimen WO-F-6-1

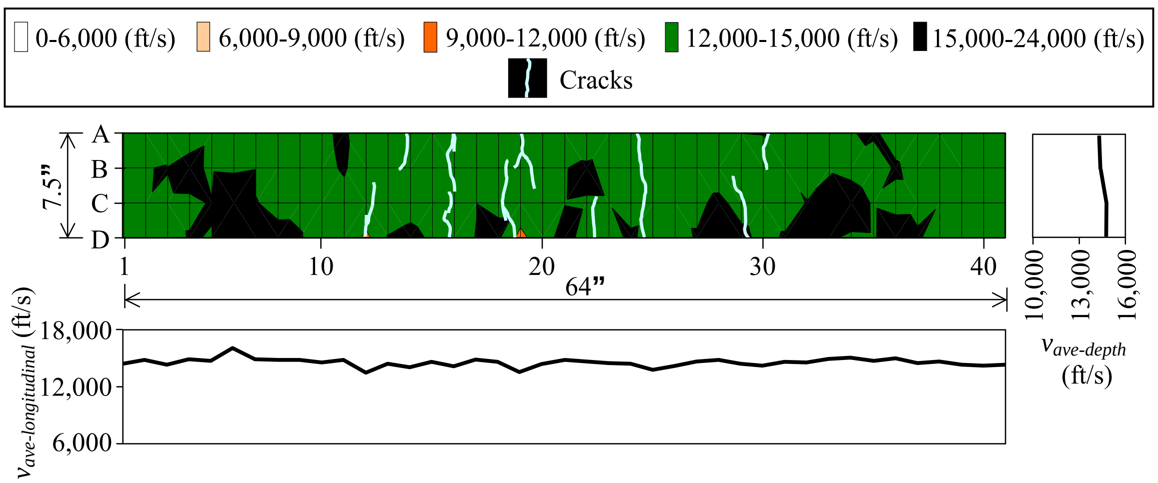


Figure 5.85. Through-transmission test results for slice from specimen WO-F-6-2

A summary of through-transmission test results for control specimens and freeze/thaw specimens without SIPMF is presented in Figure 5.86. The average percentages of measurement points for the control specimens without SIPMF were 1% very poor, 3% poor, 11% moderate to questionable, 81% good, and 4% very good. The average percentages of measurement points for the 300-cycle freeze/thaw specimens without SIPMF were 0% very poor, 2% poor, 10% moderate to questionable, 85% good, and 3% very good. The average percentages of measurement points for the 600-cycle freeze/thaw specimens without SIPMF were 0% very poor, 0% poor, 2% moderate to questionable, 81% good, and 17% very good.

The average pulse velocity for the entire cross sections of the freeze/thaw specimens without SIPMF increased to 13,360 ft/s after 300 cycles of freeze/thaw exposure (compared to 13,244 ft/s for control specimens). A subsequent increase in average pulse velocity to 14,457 ft/s was measured for the 600 cycle specimens. The overall increase in pulse velocity after freeze/thaw exposure is attributed to improved hydration conditions in the presence of frequent wetting of the specimens.

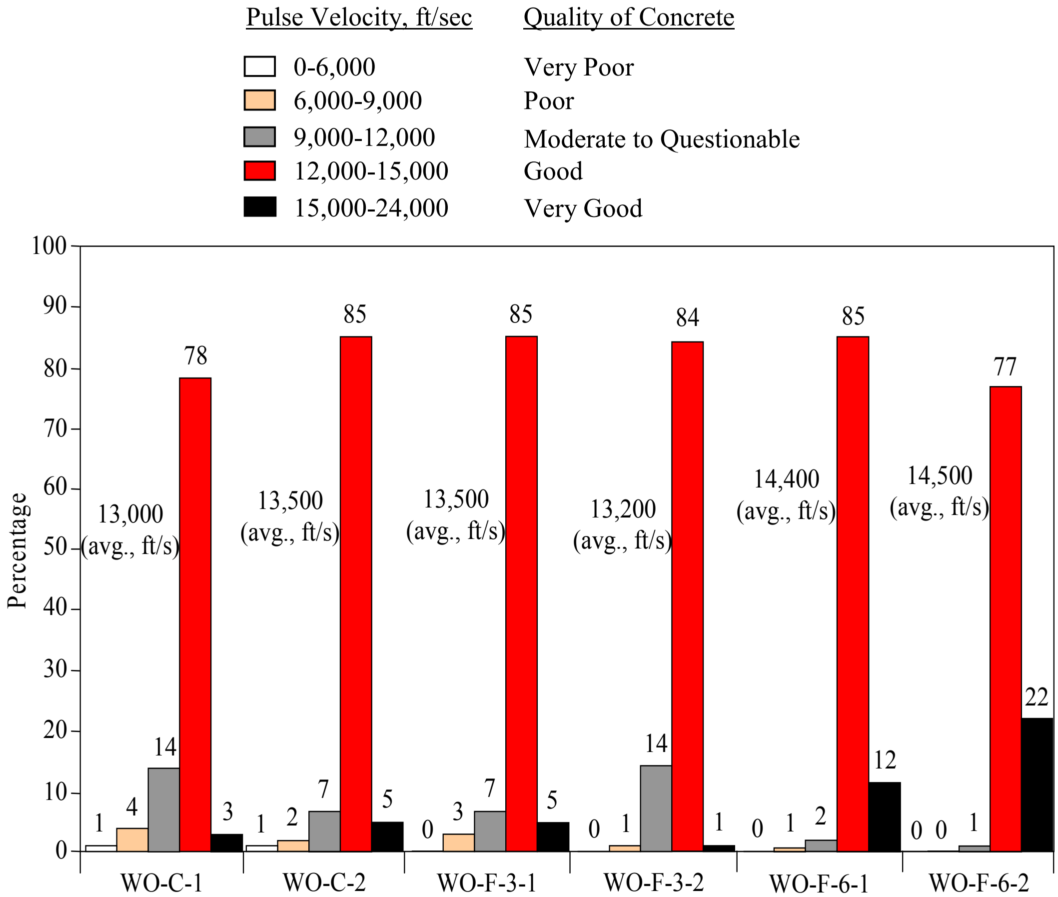


Figure 5.86. Summary of through-transmission test results for control and freeze/thaw specimens without SIPMF

Salt-Water Specimens

Through-transmission test results for 1,000-hour salt-water exposures specimens without SIPMF are presented in Figures 5.87 and 5.88. The average ultrasonic velocity for the entire cross sections of 1,000-hour salt-water exposures specimens without SIPMF was 14,087 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 1,000-hour salt-water exposures specimens without SIPMF was 14,052 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 1,000-hour salt-water exposures specimens without SIPMF was 14,124 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 1,000-hour salt-water exposures specimens without SIPMF was 14,061 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 1,000-hour salt-water exposures specimens without SIPMF.

Through-transmission test results for 3,000-hour salt-water exposures specimens without SIPMF are presented in Figures 5.89 and 5.90. The average ultrasonic velocity for the entire cross sections of 3,000-hour salt-water exposures specimens without SIPMF was 14,449 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 3,000-hour salt-water exposures specimens without SIPMF was 14,500 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 3,000-hour salt-water exposures specimens without SIPMF was 14,394 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 3,000-hour salt-water exposures specimens without SIPMF was 14,754 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 3,000-hour salt-water exposures specimens without SIPMF.

Through-transmission test results for 10,000-hour salt-water exposures specimens without SIPMF are presented in Figures 5.91 and 5.92. The average ultrasonic velocity for the entire cross sections of 10,000-hour salt-water exposures specimens without SIPMF was 14,581 ft/sec. The average ultrasonic velocity for the points on the perimeter (rows A and D and points: B1, C1, B41, and C41) for 10,000-hour salt-water exposures specimens without SIPMF was 14,649 ft/sec. The average ultrasonic velocity for the interior points (rows B and C except points: B1, C1, B41, and C41) for 10,000-hour salt-water exposures specimens without SIPMF was 14,506 ft/sec. The average ultrasonic velocity for the bottom points (rows D) for 10,000-hour salt-water exposures specimens without SIPMF was 14,787 ft/sec. Essentially, the distribution of pulse velocity over the cross section is uniform for the 10,000-hour salt-water exposures specimens without SIPMF.

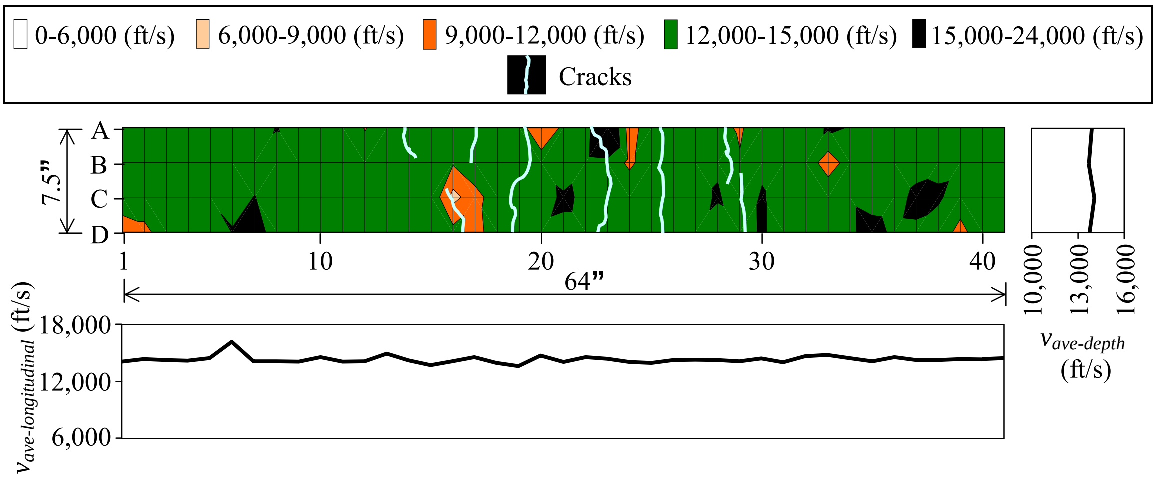


Figure 5.87. Through-transmission test results for slice from specimen WO-S-1-1

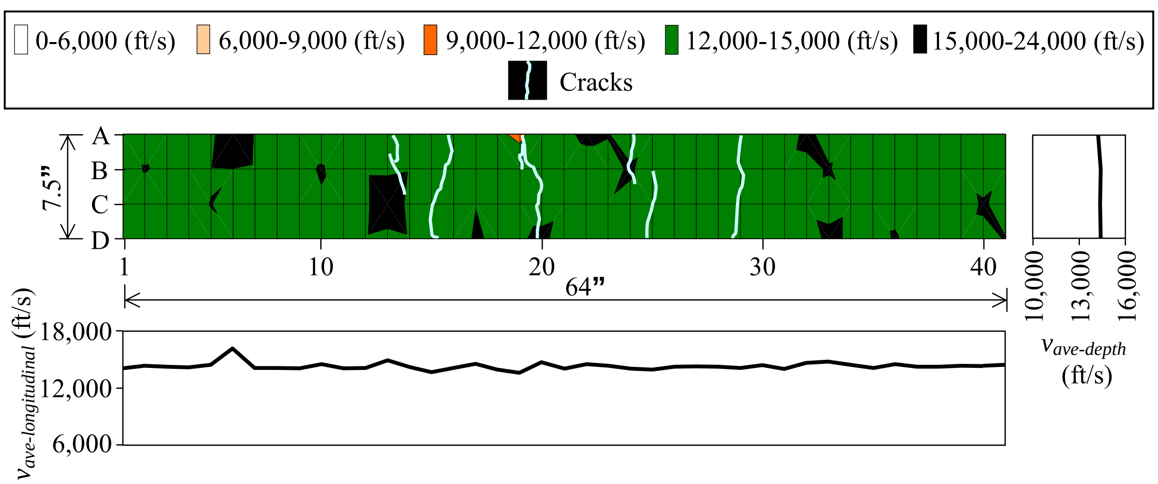


Figure 5.88. Through-transmission test results for slice from specimen WO-S-1-2

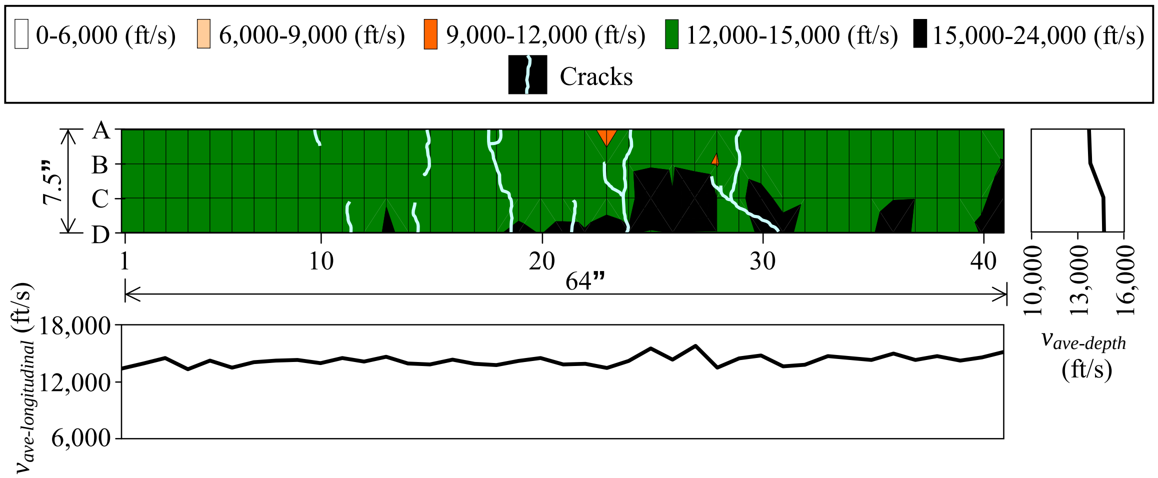


Figure 5.89. Through-transmission test results for slice from specimen WO-S-3-1

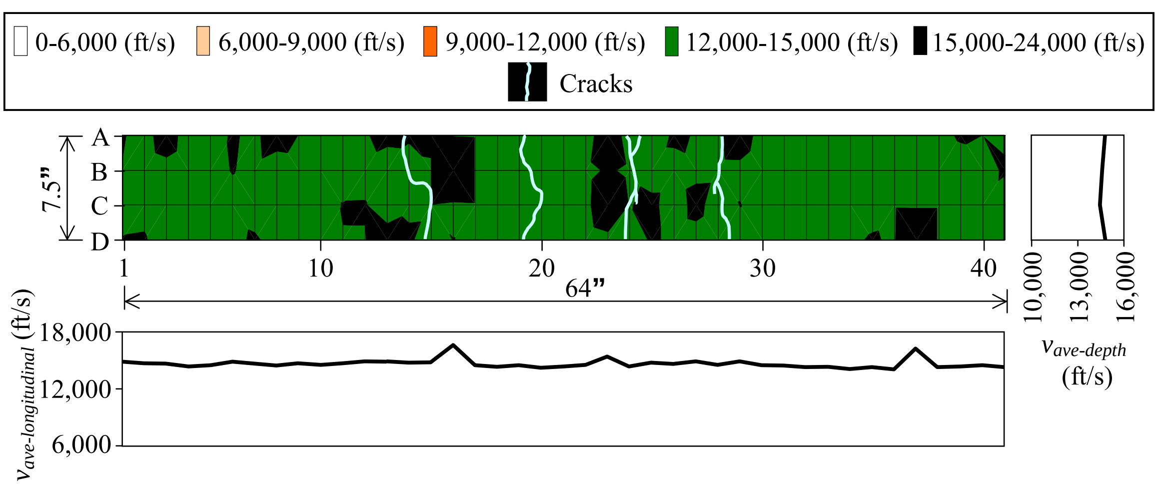


Figure 5.90. Through-transmission test results for slice from specimen WO-S-3-2

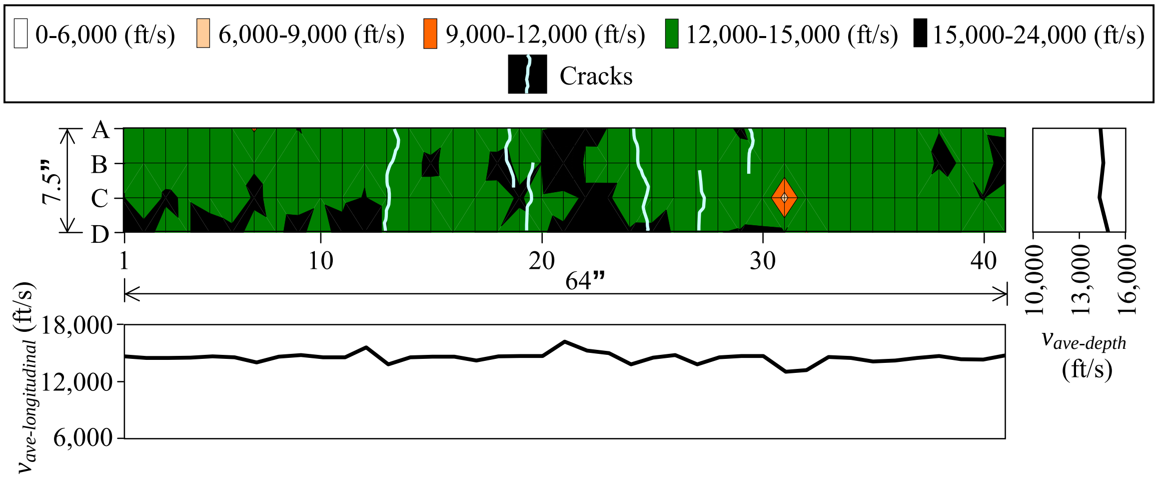


Figure 5.91. Through-transmission test results for slice from specimen WO-S-10-1

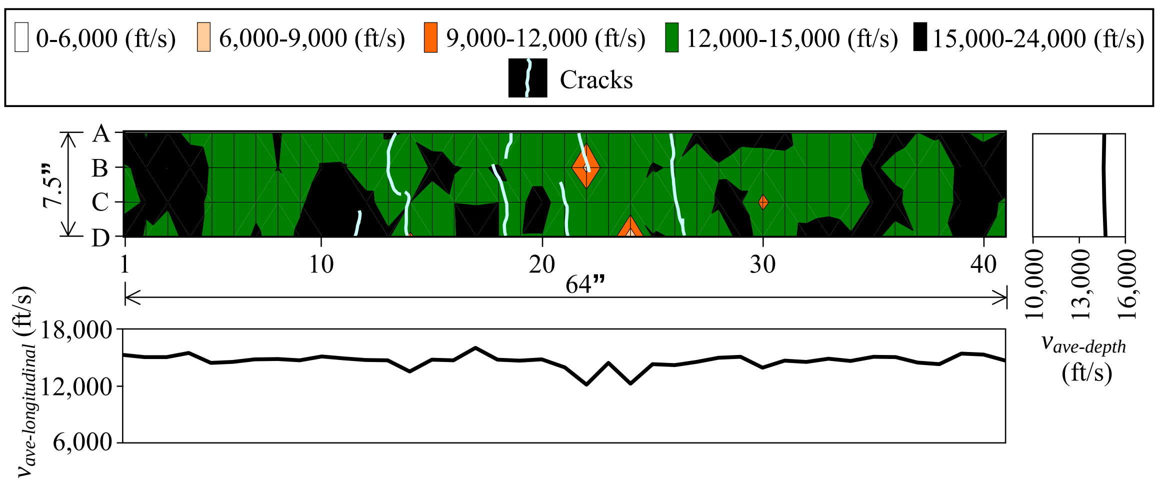


Figure 5.92. Through-transmission test results for slice from specimen WO-S-10-2

A summary of through-transmission test results for control specimens and salt-water specimens without SIPMF is presented in Figure 5.93. The average percentages of measurement points for the control specimens without SIPMF were 1% very poor, 3% poor, 11% moderate to questionable, 81% good, and 4% very good. The average percentages of measurement points for the 1,000-hour salt-water exposures specimens without SIPMF were 0% very poor, 1% poor, 3% moderate to questionable, 87% good, and 9% very good. The average percentages of measurement points for the 3,000-hour salt-water exposures specimens without SIPMF were 0% very poor, 0% poor, 1% moderate to questionable, 85% good, and 15% very good. The average percentages of measurement points for the 10,000-hour salt-water exposures specimens without

SIPMF were 0% very poor, 1% poor, 1% moderate to questionable, 70% good, and 27% very good.

The average pulse velocity for the entire cross sections of the salt-water exposures specimens without SIPMF increased to 14,087 ft/s after 1,000-hour of salt-water exposure (compared to 13,244 ft/s for control specimens). The average pulse velocity for the entire cross sections increased monotonically and fraction of "very good" concrete is increasing with further salt-water exposure (14,449 ft/s for the 3,000-hour salt-water specimens and 14,581 ft/s for the 10,000-hour salt-water specimens). The consistent increase in pulse velocity after salt-water exposure is attributed to improved hydration conditions for specimens submerged in a tank.

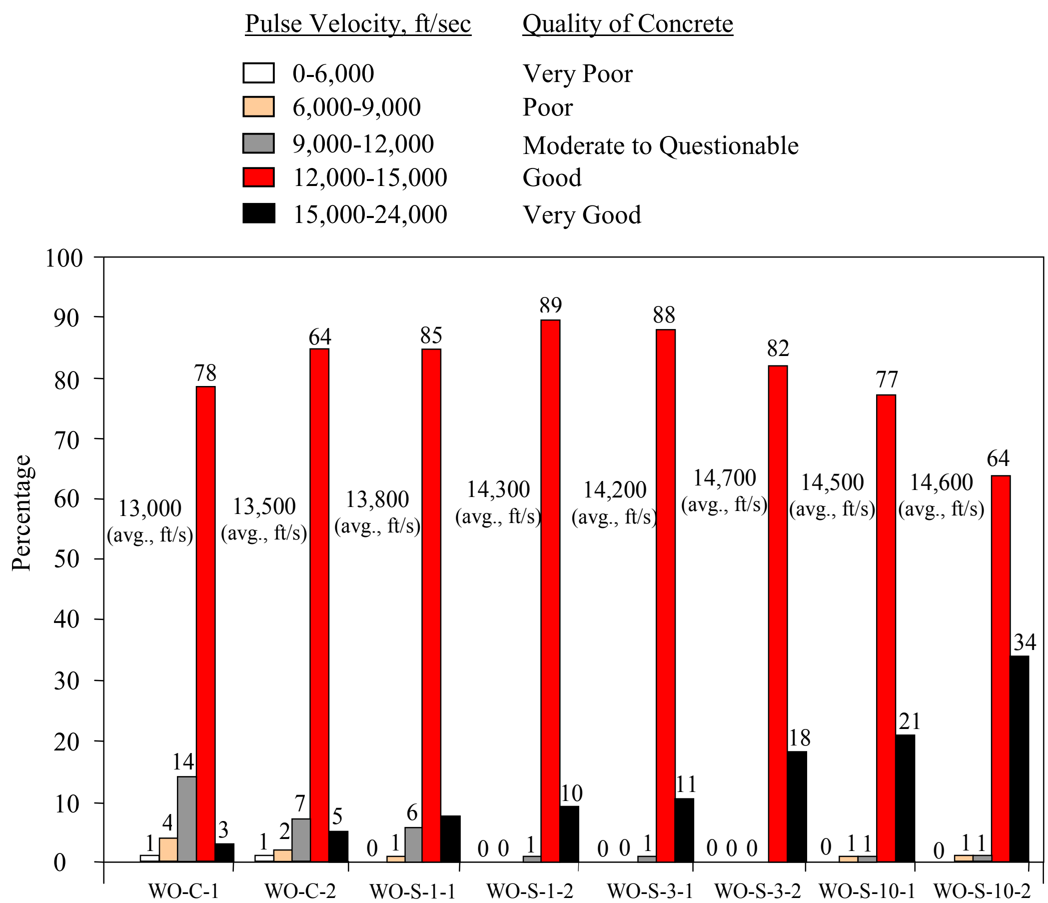


Figure 5.93. Summary of through-transmission test results for control and salt-water exposure specimens without SIPMF

5.4.3 Ultimate Load Test Results

Ultimate load test was applied on each specimen at the end of the environmental exposures, and the load setup "T" was used for ultimate load. Ultimate load test results are presented for control specimens, freeze/thaw specimens, and salt-water specimens without SIPMF in this section. For ultimate load tests on specimens with SIPMF, failure modes observed were flexural, shear, and flexural/shear (Figure 5.94).

a. Flexural failure mode

b. Shear failure mode

c. Flexural/shear failure mode

Figure 5.94. Modes of failure for specimens without SIPMF

Control Specimens

The ultimate load tests were conducted for control specimens without SIPMF after 287 days of curing (WO-C-1) and 568 days of curing (WO-C-2). The failure mode for WO-C-1 specimen was a flexural/shear failure mode whereas the failure mode for WO-C-2 specimen was a flexural failure mode. The ulitmate load was 24.02 kips and the deflection corresponding to peak load was 1.11 in. for WO-C-1. The ultimate load was 24.04 kips, and the deflection corresponding to peak load was 1.00 in. for WO-C-2. Graphical and tabular summaries of the control specimen results are presented in comparison to the environmental exposure tests in the following sections.

No additional strength was achieved over the extended curing period for WO-C-2. The ultimate load of control specimens was estimated using either the strength design method for flexural capacity or the shear strength calculation for shear capacity and the results from corresponding compressive strength (cylinder) tests. The predicted strengths for the control specimens were 23.70 kips/ 24.1 kips (flexural/shear) for WO-C-1 and 23.65 kips/ 23.63 kips (flexural/shear) for WO-C-2, respectively. Generally, good agreement is observed between predicted and experimental results.

Results from the control specimens were used as baseline values for comparison to the specimens that were subjected to environmental exposure. Ultimate load tests were conducted on the control specimens on dates that coincided with tests for the shortest environmental exposure conditions (1,000 hour salt-water exposure) and for the longest environmental exposure conditions (10,000 hour salt-water exposure) to account for expected changes in baseline strength with time due to curing. Linear interpolation was applied to data from the control specimens to estimate baseline values for comparative tests conducted at intermediate stages (300 and 600 freeze/thaw cycle and 3,000 hour salt-water specimens) [Figure 5.95].

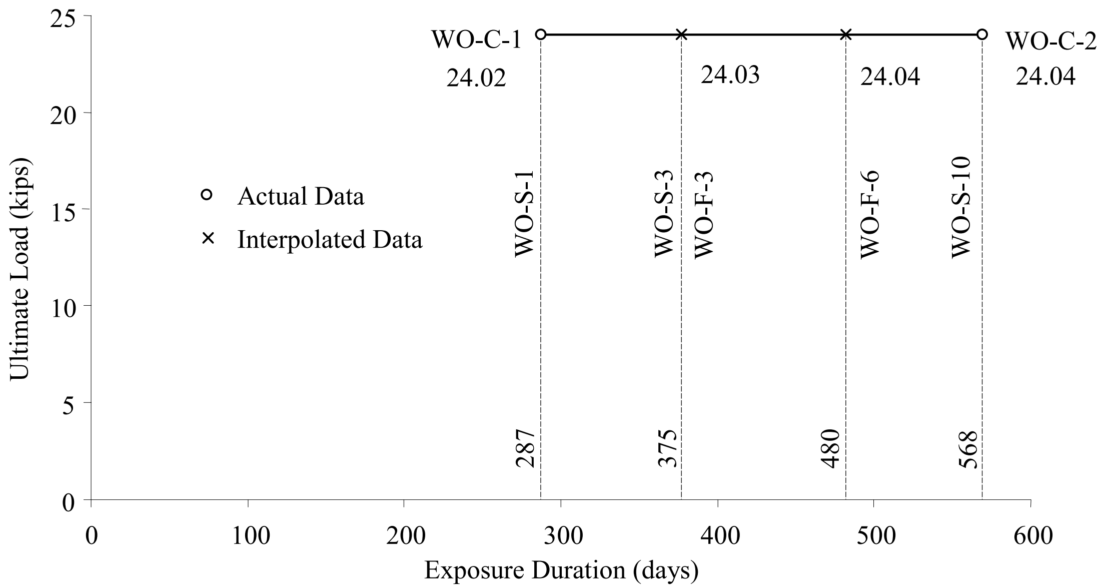


Figure 5.95. Interpolation of control values for freeze/thaw and salt-water specimens without SIPMF

Freeze/Thaw Specimens

The ultimate load tests were conducted for Freeze/Thaw specimens without SIPMF after 375 days of curing (300 cycles) and 480 days of curing (600 cycles). The failure mode for all freeze/thaw specimens was flexural failure mode with the exception of WO-F-6-1 which failed in flexural/shear failure mode. For WO-F-3-1, the ultimate load was 22.66 kips and the deflection corresponding to peak load was 1.11 in. For WO-F-3-2, the ultimate load was 24.91 kips and the deflection corresponding to peak load was 0.77 in. For WO-F-6-1, the ultimate load was 23.89 kips and the deflection corresponding to peak load was 0.65 in. For WO-F-6-2, the ultimate load was 20.94 kips and the deflection corresponding to peak load was 0.44 in. A graph containing all ultimate load test results for freeze/thaw and control specimens without SIPMFs is presented in Figure 5.96. A summary of results is presented in Table 5.6.

A comparison was made to determine the effect of freeze/thaw exposure on ultimate load of specimens without SIPMF (Figure 5.97). Appropriate baseline values for comparison were determined from control specimens. A reduction in ultimate load as compared to baseline values was observed for all freeze/thaw specimens without SIPMFs except for WO-F-3-2. After 300 cycles of freeze/thaw exposure, a reduction in the ultimate load for WO-F-3-1 as compared to baseline value was 5.7% and an increase in the ultimate load for WO-F-3-2 as compared to baseline value was 3.7% for an average reduction of 1.0%. After 600 cycles of freeze/thaw exposure, reductions in ultimate load as compared to baseline values were 0.7% and 12.9% for an average reduction of 6.7%. These data indicate that deterioration of specimens occurs due to freeze/thaw exposure. Apparent difference is observed between 300 and 600 freeze/thaw cycles.

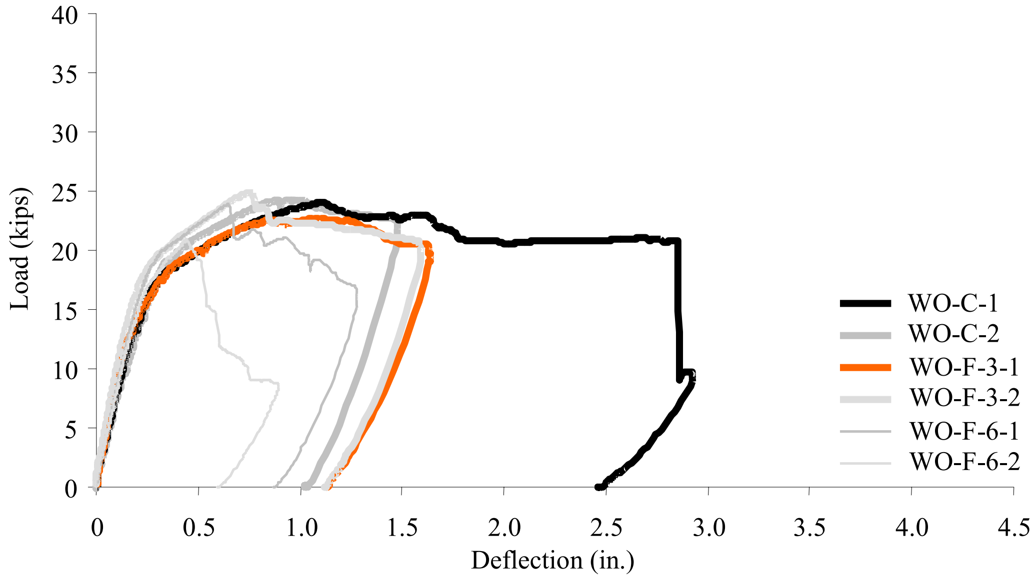


Figure 5.96. Load-deflection curves for ultimate load of 300-, 600-cycle, and control specimens without SIPMF

Table 5.6. Ultimate load results for control, 300-, and 600-cycle freeze/thaw specimens without SIPMF

Specimen	**Mode of Failure**	**Failure Load** (kips)		**Comparable Control Value** (kips)	**Deflection at Ultimate Load** (in.)	**Percentage of Change in Deflection**		**Percentage of Change in Capacity**	
WO-C-1	Flexural/ Shear	24.02	(--)	(--)	1.11	(--)		(--)	
WO-C-2	Flexural	24.04			1.00				
WO-F-3-1	Flexural	22.66	Average 23.79	24.03[a]	1.11	+ 3.2%	-12.6%	- 5.7%	Average - 1.0%
WO-F-3-2	Flexural	24.91			0.77	-28.4%		+ 3.7%	
WO-F-6-1	Flexural	23.89	Average 22.42	24.04[a]	0.65	-37.1%	-47.3%	- 0.7%	Average - 6.7%
WO-F-6-2	Shear	20.94			0.44	-57.4%		- 12.9%	

[a] Linear interpolation used between control specimens to estimate baseline value

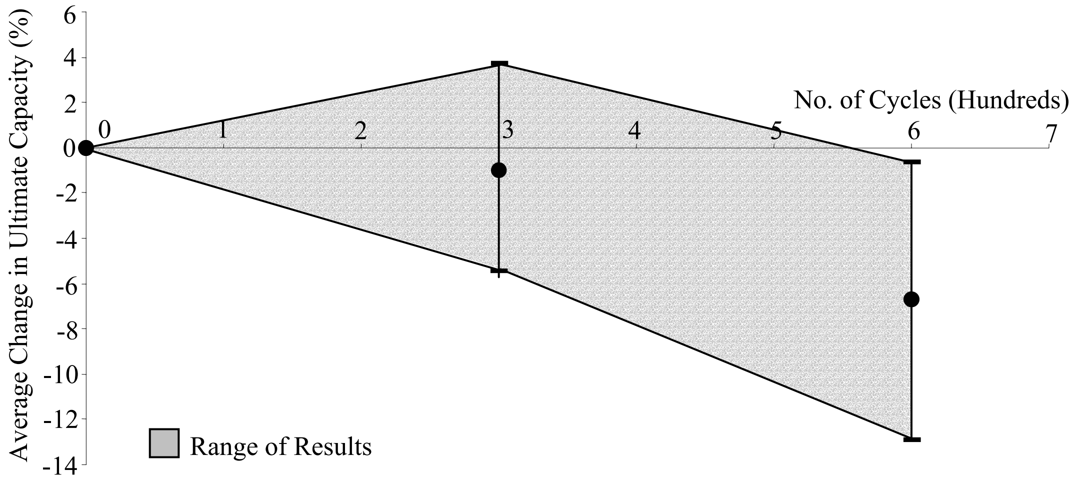


Figure 5.97. Percentage of change in ultimate load carrying capacity for freeze/thaw exposure specimens without SIPMF

Salt-Water Specimens

The ultimate load tests were conducted for Salt-Water specimens without SIPMF after 287 days of curing (1,000 hour expousre specimens), 375 days of curing (3,000 hour expsosure specimens) and 586 days of curing (10,000 hour expsosure specimens). The failure mode for all salt-water specimens was flexural failure mode with the exception of WO-S-10-1, which failed in flexural/shear failure mode. For WO-S-1-1, the ultimate load was 26.78 kips and the deflection corresponding to peak load was 1.13 in. For WO-S-1-2, the ultimate load was 25.61 kips and the deflection corresponding to peak load was 1.04 in. For WO-S-3-1, the ultimate load was 25.76 kips and the deflection corresponding to peak load was 0.87 in. For WO-S-3-2, the ultimate load was 25.64 kips and the deflection corresponding to peak load was 0.82 in. For WO-S-10-1, the ultimate load was 25.02 kips and the deflection corresponding to peak load was 0.79 in. For WO-S-10-2, the ultimate load was 25.73 kips and the deflection corresponding to peak load was 0.87 in. A graph containing all ultimate load test results for salt-water and control specimens without SIPMFs is presented in Figure 5.98. A summary of results is presented in Table 5.7.

A comparison was made to determine the effect of salt-water exposure on ultimate load of specimens without SIPMF (Figure 5.99). Appropriate baseline values for comparison were determined from control specimens. An initial increase in ultimate load is observed after 1,000 hours of salt-water exposure as compared to baseline values followed by a lesser amount of increase in ultimate load due to further salt-water exposure. After 1,000 hours of salt-water exposure, increases in ultimate load as compared to baseline values were 11.4% and 6.6% for an average increase of 9.0%. After 3,000 hours of salt-water exposure, increases in ultimate load as compared to baseline values were 7.2% and 6.7% for an average increase of 7.0%. After 10,000 hours of salt-water exposure, further increases in ultimate load as compared to baseline values were observed as 4.1% and 7.1% for an average increase of 5.6%. These data indicate that structural improvement of specimens occurs due to salt-water exposure. The observed increase in ultimate load was most prominent for specimens exposed to 1,000 hours of salt-water.

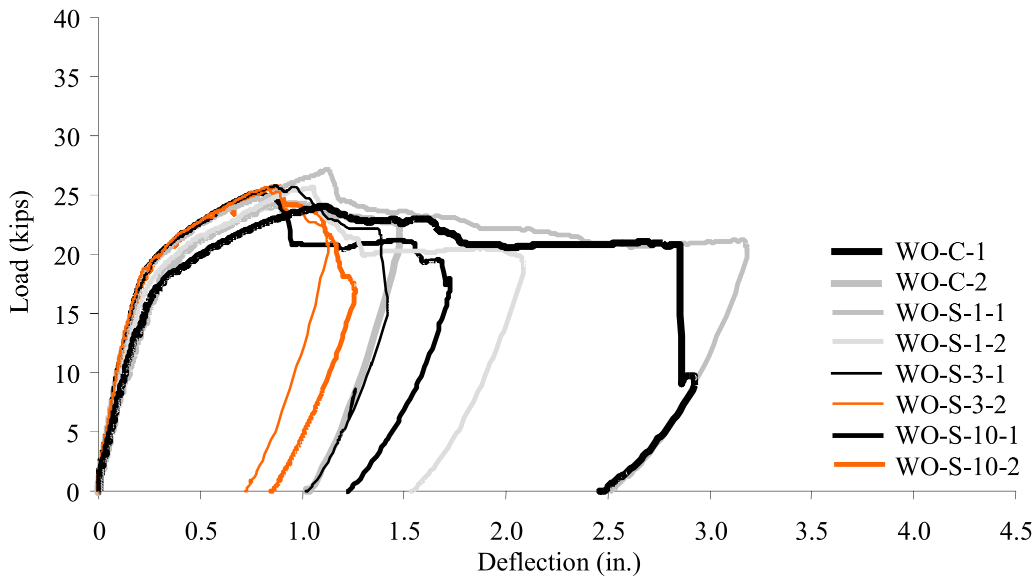


Figure 5.98. Load-deflection curves for ultimate load of 1,000-, 3,000-, 10,000-hour salt-water exposures, and control specimens without SIPMF

Table 5.7. Ultimate load results for control, 1,000-, 3,000-, 10,000-hour salt-water exposures specimens without SIPMF

Specimen	**Mode of Failure**	**Failure Load** (kips)		**Comparable Control Value** (kips)	**Deflection at Ultimate Load** (in.)	**Percentage of Change in Deflection**		**Percentage of Change in Capacity**	
WO-C-1	Flexural/ Shear	24.02	(--)	(--)	1.11	(--)		(--)	
WO-C-2	Flexural	24.04			1.00				
WO-S-1-1	Flexural	26.78	Average 26.20	24.02	1.13	1.8%	-2.3%	+ 11.4%	Average + 9.0%
WO-S-1-2	Flexural	25.61			1.04	-6.3%		+ 6.58%	
WO-S-3-1	Flexural	25.76	Average 25.70	24.03[a]	0.87	-19.1%	-21.5%	+ 7.20%	Average + 7.0%
WO-S-3-2	Flexural	25.64			0.82	-23.8%		+ 6.70%	
WO-S-10-1	Flexural/ Shear	25.02	Average 25.38	24.04	0.79	-21.0%	-17.0%	+ 4.12%	Average + 5.6%
WO-S-10-2	Flexural	25.73			0.87	-13.0%		+ 7.07%	

[a] Linear interpolation used between control specimens to estimate baseline value

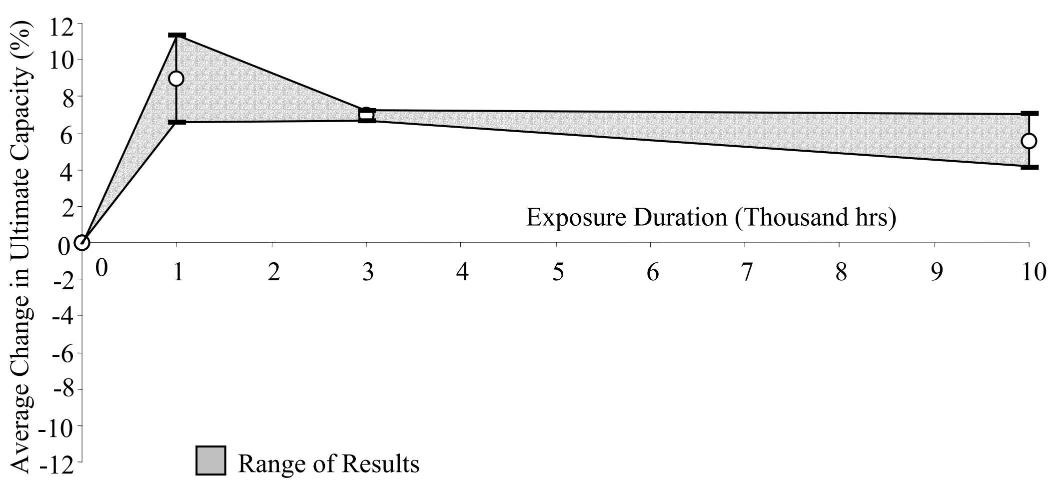


Figure 5.99. Percentage of change in ultimate load carrying capacity for salt-water exposures specimens without SIPMF

5.5 COMPARISON BETWEEN SPECIMENS WITH AND WITHOUT SIPMF

5.5.1 Ultrasonic Through-Transmission Results Comparison

Comparisons of the results of the ultrasonic through-transmission tests are presented as bar charts representing the numerical distribution of pulse-velocities for all measurement points. A summary bar chart for the comparison between the ranges for control specimens with and without SIPMF is presented in Figure 5.100. A summary bar chart for the comparison between the ranges for 300-cycle freeze/thaw specimens with and without SIPMF is presented in Figure 5.101. A summary bar chart for the comparison between the ranges for 600-cycle freeze/thaw specimens with and without SIPMF is presented in Figure 5.102. A summary bar chart for the comparison between the ranges for 1,000-hour salt-water exposures specimens with and without SIPMF is presented in Figure 5.103. A summary bar chart for the comparison between the ranges for 3,000-hour salt-water exposures specimens with and without SIPMF is presented in Figure 5.104. A summary bar chart for the comparison between the ranges for 10,000-hour salt-water exposures specimens with and without SIPMF is presented in Figure 5.105. The average velocities for the perimeter, interior, bottom, and total points of the control, freeze/thaw, and salt-water specimens with and without SIPMF are presented in Table 5.8.

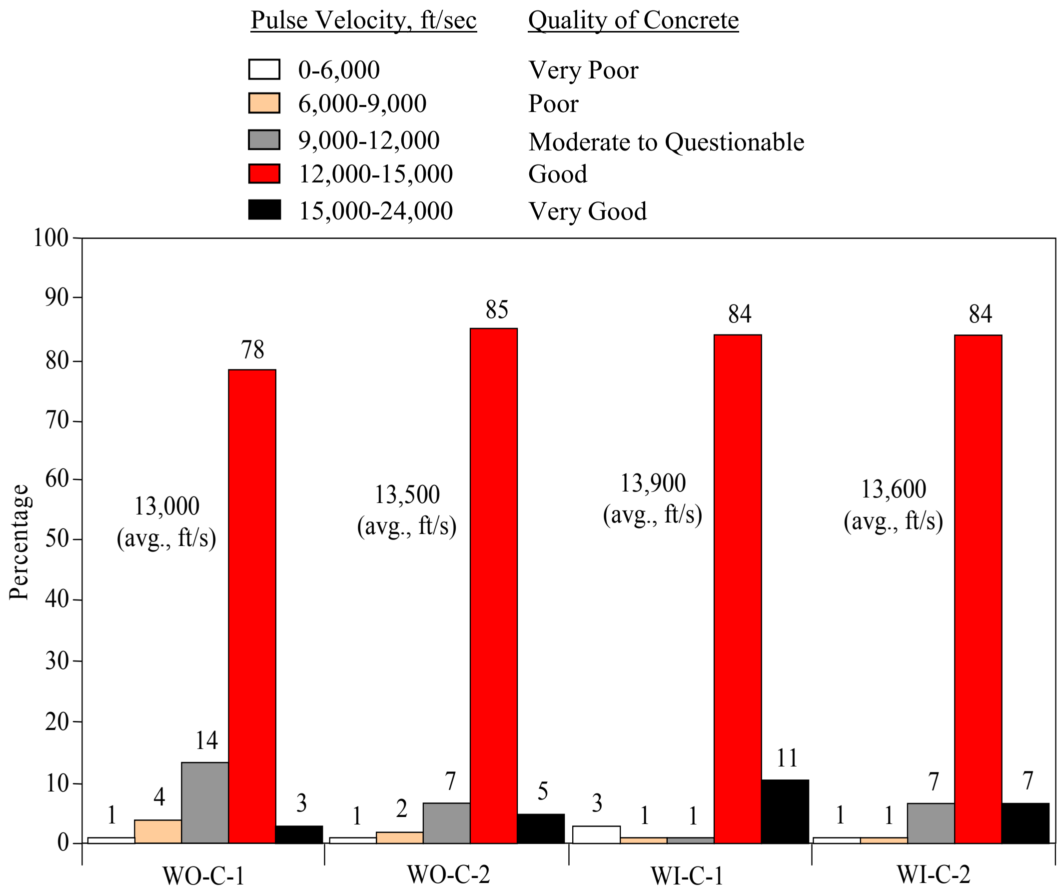


Figure 5.100. Summary of through-transmission test results for control specimens with and without SIPMF

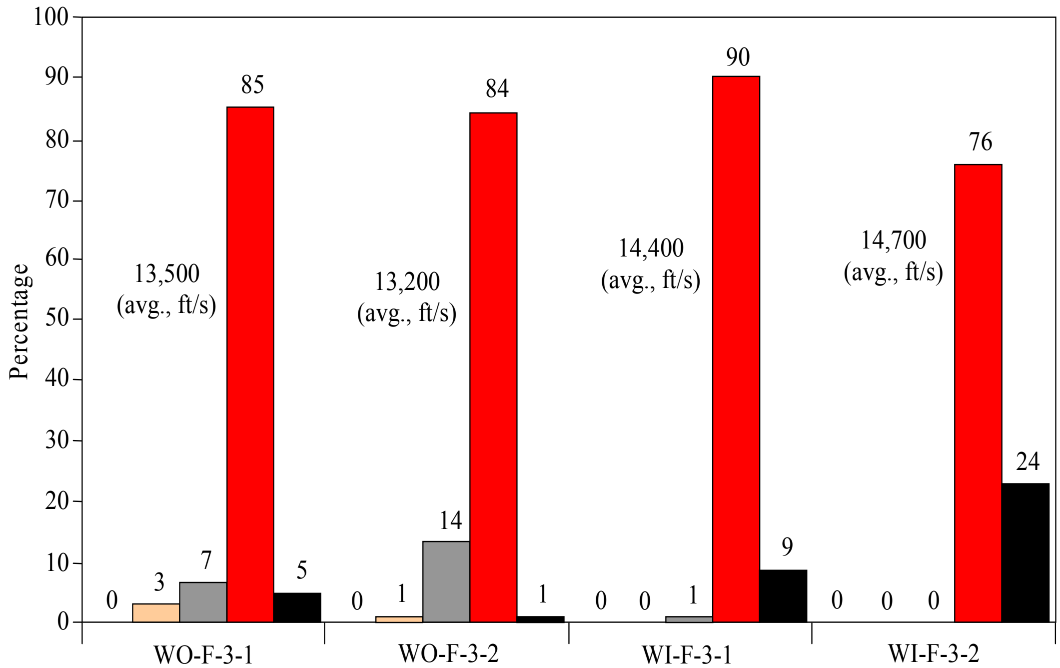


Figure 5.101. Summary of through-transmission test results for 300-cycle freeze/thaw specimens with and without SIPMF

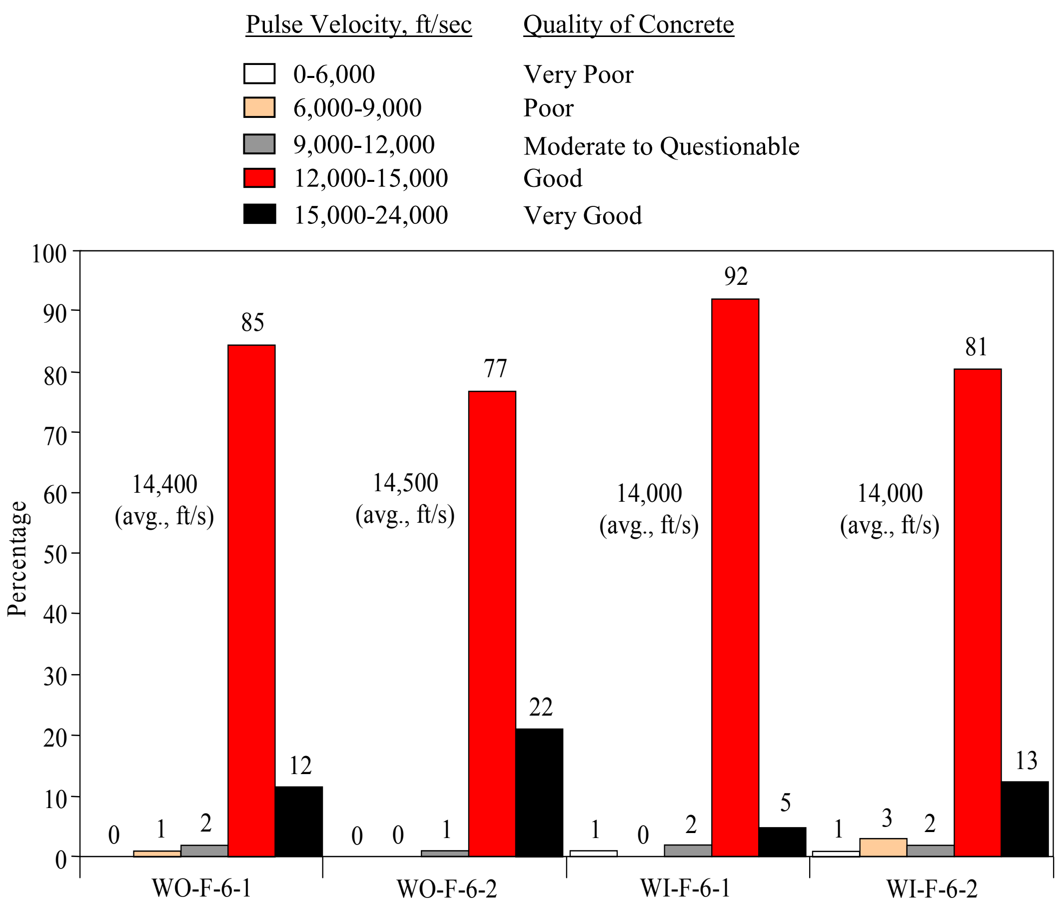


Figure 5.102. Summary of through-transmission test results for 600-cycle freeze/thaw specimens with and without SIPMF

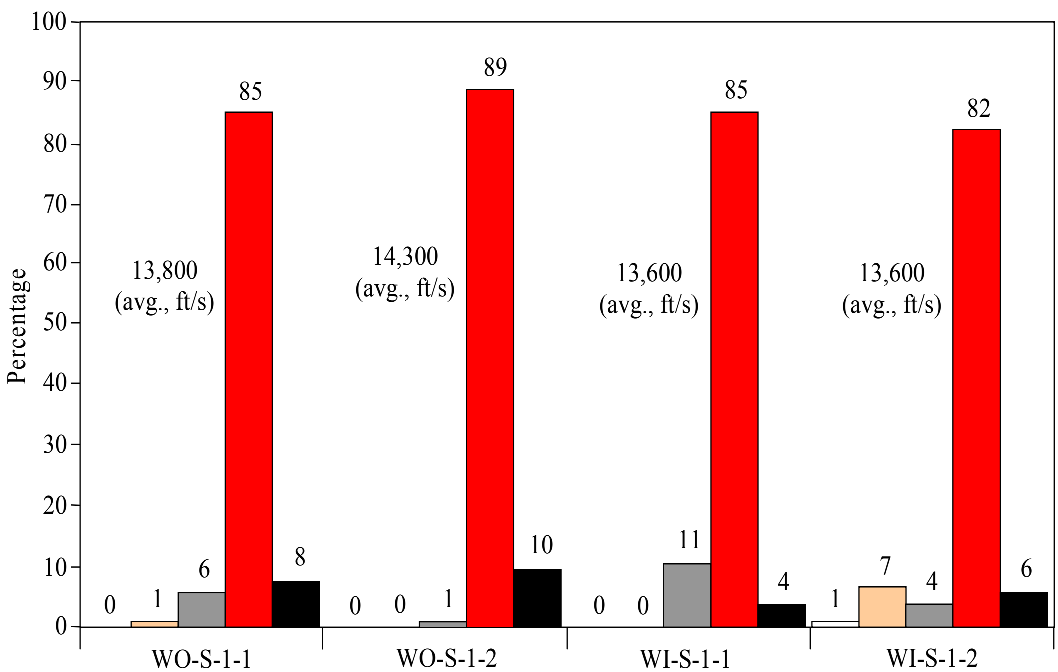


Figure 5.103. Summary of through-transmission test results for 1,000-hour salt-water exposures specimens with and without SIPMF

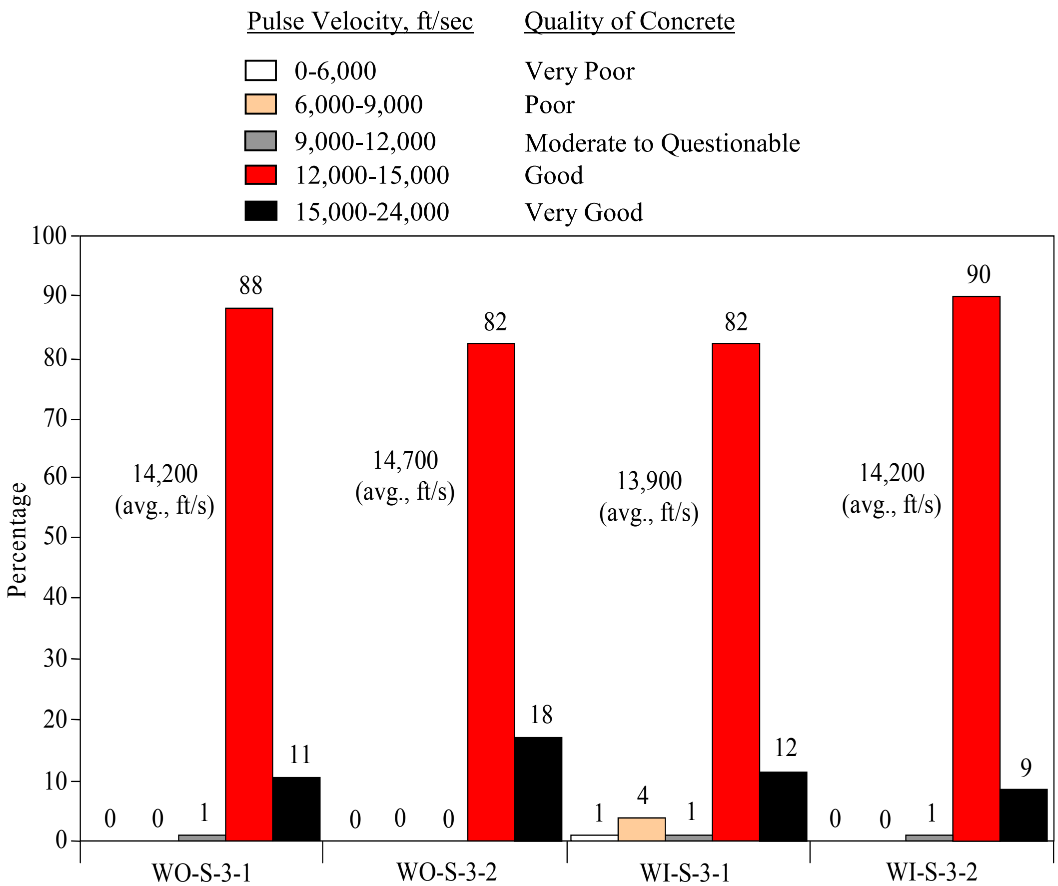


Figure 5.104. Summary of through-transmission test results for 3,000-hour salt-water exposures specimens with and without SIPMF

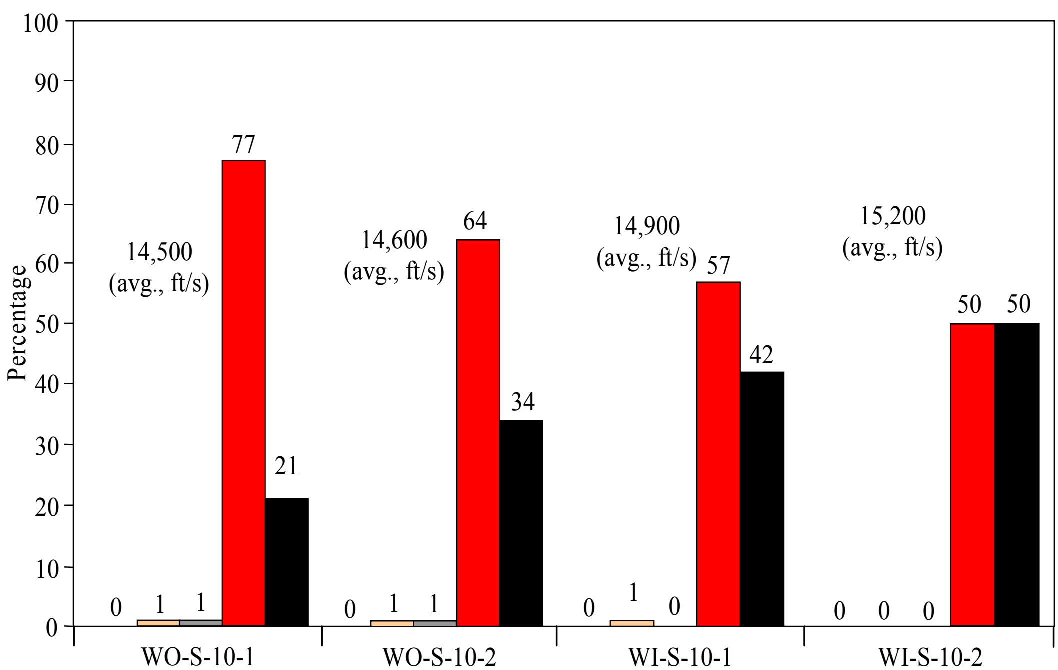
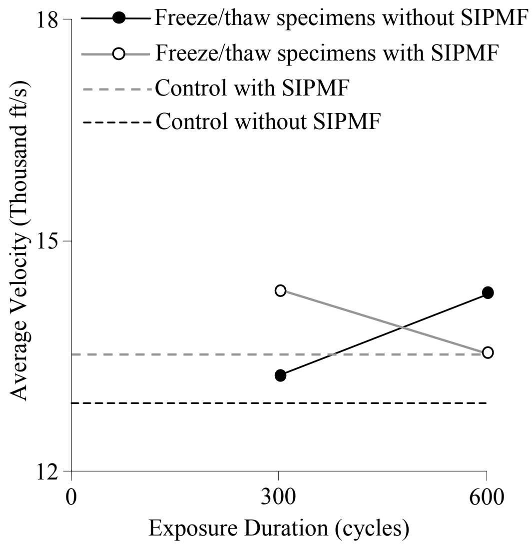


Figure 5.105. Summary of through-transmission test results for 10,000-hour salt-water exposures specimens with and without SIPMF

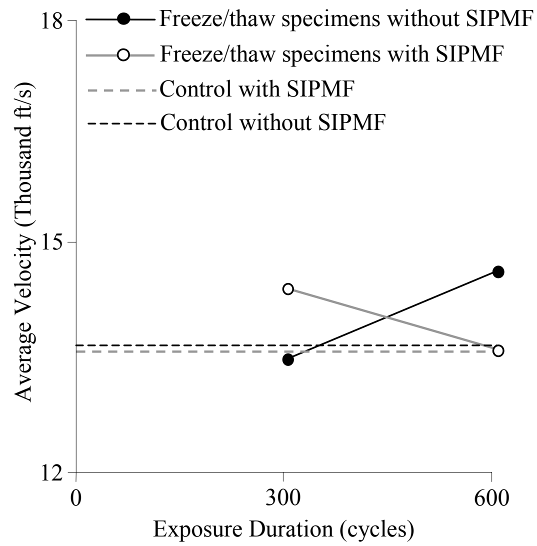
Table 5.8. Average velocities for the control, freeze/thaw, and salt-water specimens with and without SIPMF

Type of specimens				Average Velocity (ft/s)							
				Perimeter Points		Interior Points		Bottom Points		Total Points	
				Specimen	Avrg.	Specimen	Avrg.	Specimen	Avrg.	Specimen	Avrg.
Specimens with SIPMF	**Control**		**WI-C-1**	13,746	13,577	14,047	13,891	13,922	13,663	13,889	13,727
			WI-C-2	13,408		13,735		13,404		13,564	
	Freeze/Thaw	**300 cycle**	**WI-F-3-1**	14,229	14,384	14,513	14,681	14,677	14,742	14,364	14,525
			WI-F-3-2	14,538		14,849		14,806		14,686	
		600 cycle	**WI-F-6-1**	13,640	13,595	14,360	14,404	14,129	13,412	13,982	13,979
			WI-F-6-2	13,549		14,447		12,696		13,976	
	Salt-Water	**1,000 hr**	**WI-S-1-1**	13,523	13,487	13,631	13,673	13,857	13,275	13,574	13,575
			WI-S-1-2	13,450		13,714		12,694		13,575	
		3,000 hr	**WI-S-3-1**	13,779	14,081	13,972	14,029	13,489	13,876	13,871	14,056
			WI-S-3-2	14,382		14,085		14,263		14,241	
		10,000 hr	**WI-S-10-1**	14,916	14,987	14,953	15,067	15,153	15,198	14,934	15,025
			WI-S-10-2	15,057		15,180		15,244		15,115	
Specimens without SIPMF	**Control**		**WO-C-1**	12,576	12,894	13,501	13,619	11,951	12,535	13,027	13,244
			WO-C-2	13,211		13,737		13,119		13,461	
	Freeze/Thaw	**300 cycle**	**WO-F-3-1**	13,351	13,279	13,648	13,449	14,257	13,853	13,492	13,360
			WO-F-3-2	13,207		13,249		13,448		13,227	
		600 cycle	**WO-F-6-1**	14,151	14,324	14,610	14,600	14,410	14,575	14,373	14,457
			WO-F-6-2	14,497		14,589		14,741		14,540	
	Salt-Water	**1,000 hr**	**WO-S-1-1**	13,823	14,052	13,877	14,124	13,747	14,061	13,849	14,087
			WO-S-1-2	14,281		14,371		14,375		14,324	
		3,000 hr	**WO-S-3-1**	14,219	14,500	14,256	14,394	14,704	14,754	14,236	14,449
			WO-S-3-2	14,780		14,531		14,803		14,662	
		10,000 hr	**WO-S-10-1**	14,615	14,649	14,427	14,506	14,865	14,787	14,526	14,581
			WO-S-10-2	14,683		14,584		14,709		14,636	

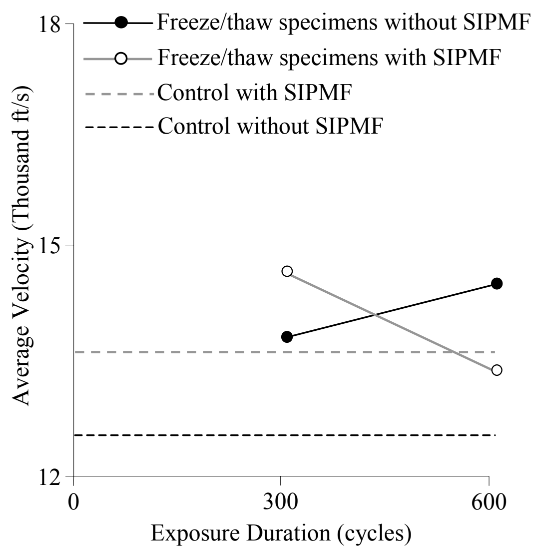
The graphs for the comparison between the average velocities for the perimeter, interior, bottom, and total points of the control and freeze/thaw specimens with and without SIPMF are shown in Figure 5.106. A comparison of average rates of change for pulse velocity is presented in Table 5.9 for freeze/thaw exposure for specimens with and without SIPMF. The rates of change for pulse velocity are calculated from slopes of the average curves in Figure 5.106. The rates of change in pulse velocity for specimens with and without SIPMF for the period between zero and 300 freeze/thaw cycles were positive (indicating an apparent improvement in the quality of concrete). The rate of change in pulse velocity was greater for specimens with SIPMF for this period. For the period between 300 and 600 freeze/thaw cycles, the rate of change was negative for specimens with SIPMF and positive for specimens without SIPMF.



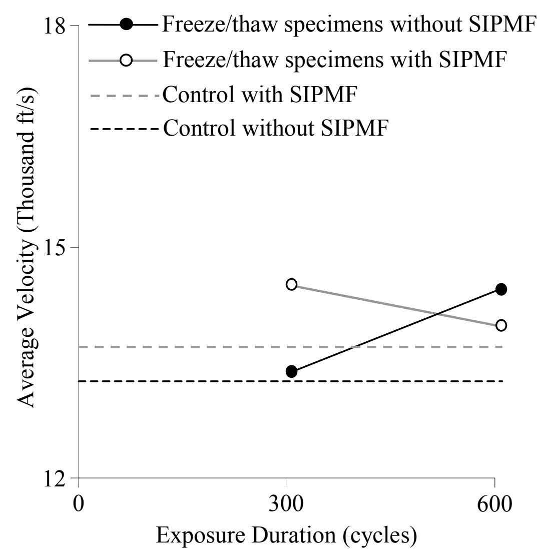
a. Average velocity for perimeter points



b. Average velocity for interior points



c. Average velocity for bottom points



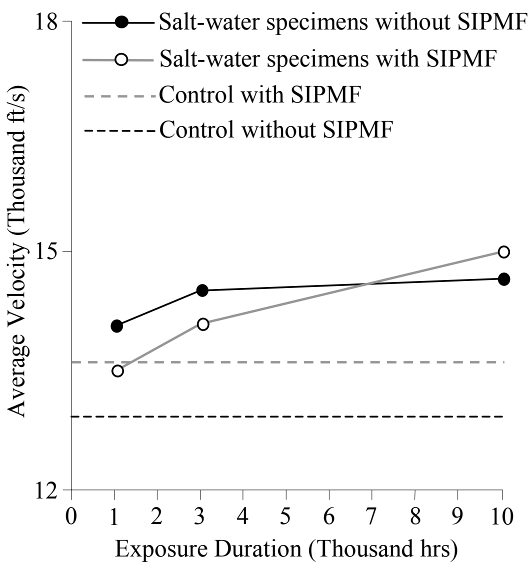
d. Average velocity for total points

Figure 5.106. Average velocity for freeze/thaw exposure specimens

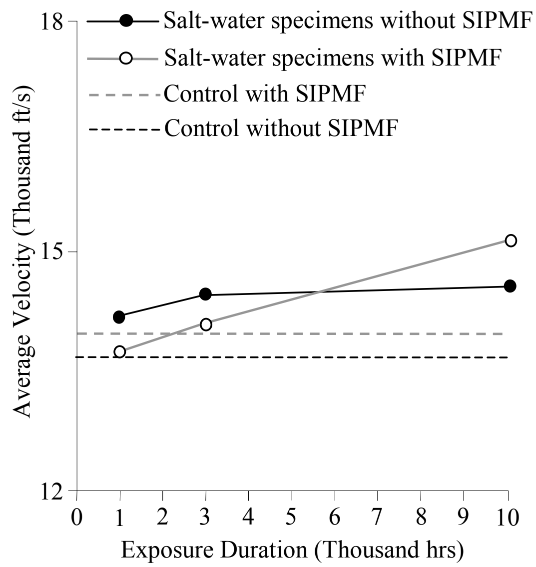
Table 5.9. Rates of change of pulse velocity for freeze/thaw exposure for specimens with and without SIPMF

Freeze/Thaw Exposure period	Rate of Change of Pulse Velocity [(ft/s) / cycle]	
	SIPMF	No SIPMF
0 to 300 cycles	+ 2.7	+ 0.4
300 to 600 cycles	- 1.8	+ 3.7

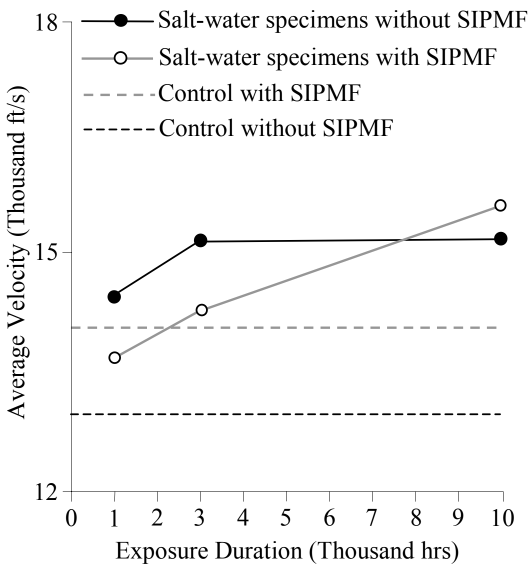
The graphs for the comparison between the average velocities for the perimeter, interior, bottom, and total points of the control and salt-water specimens with and without SIPMF are shown in Figure 5.107. A comparison of average rates of change for pulse velocity is presented in Tables 5.10 for salt-water exposure for specimens with and without SIPMF. The rates of change for pulse velocity are calculated from slopes of the average curves in Figure 5.107. In most cases the rates of change in the pulse velocity were small positive values. For the period between zero and 1,000 hours, a small negative rate of change was observed for specimens with SIPMF. The average rates of change for all specimens for periods between 1,000 and 3,000 hours as well as between 3,000 and 10,000 hours were positive.



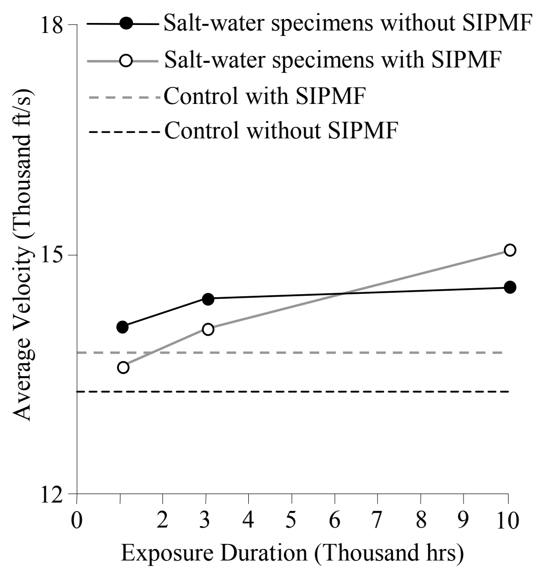
a. Average velocity for perimeter points



b. Average velocity for interior points



c. Average velocity for bottom points



d. Average velocity for total points

Figure 5.107. Average velocity for salt-water exposure specimens

Table 5.10. Rates of change of pulse velocity for salt-water exposure for specimens with and without SIPMF

Salt-Water Exposure period	**Rate of Change of Pulse Velocity** [(ft/s) / hours]	
	SIPMF	**No SIPMF**
0 to 1,000 hours	- 0.2	+ 0.8
1,000 to 3,000 hours	+ 0.2	+ 0.2
3,000 to 10,000 hours	+ 0.1	+ 0.0

5.5.2 Ultimate Load Test Results Comparison

A comparison was made to determine the effect of freeze/thaw exposure on ultimate load of specimens with and without SIPMF (Figure 5.108). Appropriate baseline values for comparison were determined from control specimens. A reduction in ultimate load as compared to baseline values was observed for all freeze/thaw specimens with and without SIPMFs except for WO-F-3-2. After 300 cycles of freeze/thaw exposure, reductions in ultimate load as compared to baseline values were greater for specimens with SIPMF than for specimens without SIPMF. In general, after 600 cycles of freeze/thaw exposure, reductions in ultimate load for all specimens with and without SIPMF, as compared to baseline values, were within the same range. These data indicate that deterioration of specimens occurs due to freeze/thaw exposure.

A comparison of average rates of change for ultimate load is presented in Table 5.11 for freeze/thaw exposure for specimens with and without SIPMF. The rates of change for ultimate load are calculated from slopes of the average curves in Figure 5.108. The rates of change in ultimate load for specimens with and without SIPMF for the period between zero and 300 freeze/thaw cycles were negative (indicating a decrease in ultimate load capacity). The rate of change in ultimate load was greater for specimens with SIPMF for this period. For the period between 300 and 600 freeze/thaw cycles, the rate of change in ultimate load was a small positive value for specimens with SIPMF and negative for specimens without SIPMF. Analysis and comparison of ductility for the specimens were not provided due to the different failure modes experienced by the specimens exposed to different environmental conditions.

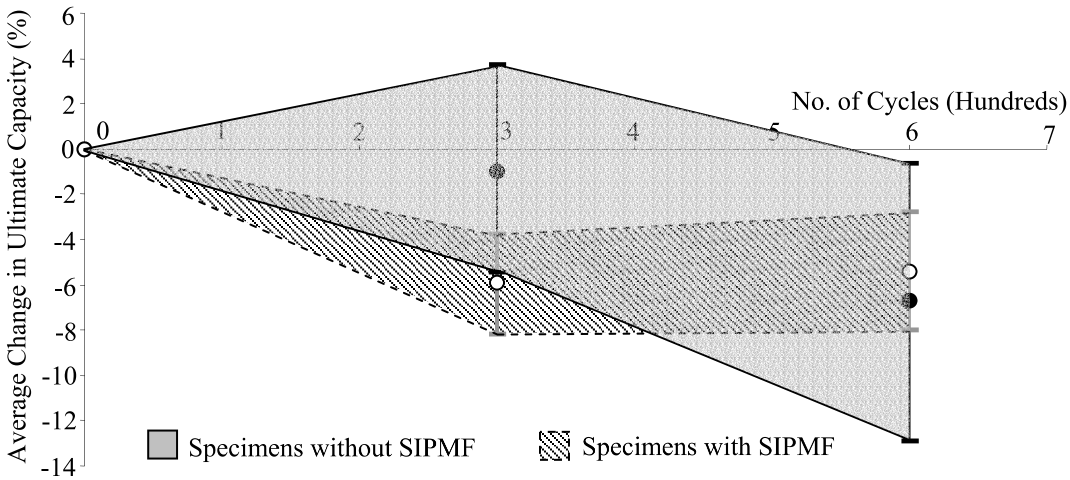


Figure 5.108. Percentage of change in ultimate load carrying capacity for freeze/thaw exposure specimens with and without SIPMF

Table 5.11. Rates of change of ultimate load for freeze/thaw exposure for specimens with and without SIPMF

Freeze/Thaw Exposure period	**Rate of Change of Ultimate Load** (% change / 100 cycles)	
	SIPMF	**No SIPMF**
0 to 300 cycles	- 2.0	- 0.3
300 to 600 cycles	+ 0.2	- 1.9

A comparison was made to determine the effect of salt-water exposure on ultimate load of specimens with and without SIPMF (Figure 5.109). Appropriate baseline values for comparison were determined from control specimens. An initial increase in ultimate load is observed after 1,000 hours of salt-water exposure as compared to baseline values followed by a lesser increase (for specimens without SIPMF) or a decrease (for specimens with SIPMF) in ultimate load due to further salt-water exposure. The average change in ultimate load carrying capacity for specimens with and without SIPMF between 3,000 and 10,000 hours of salt-water exposure was not significant. In general, the percentages of change in ultimate load carrying capacity for specimens without SIPMF are greater after salt-water exposure when compared to specimens with SIPMF.

A comparison of average rates of change for ultimate load is presented in Tables 5.12 for salt-water exposure for specimens with and without SIPMF. The rates of change for ultimate load are calculated from slopes of the average curves in Figure 5.109. The trends of the rates of change of ultimate load with salt-water exposure for specimens with and without SIPMF were similar. For both cases positive rates of change were observed from zero to 1,000 hours, negative rates of change were observed between 1,000 and 3,000 hours, and small negative rates of change were observed between 3,000 and 10,000 hours. The long-term rates of change (as measured between 3,000 and 10,000 hours) were similar.

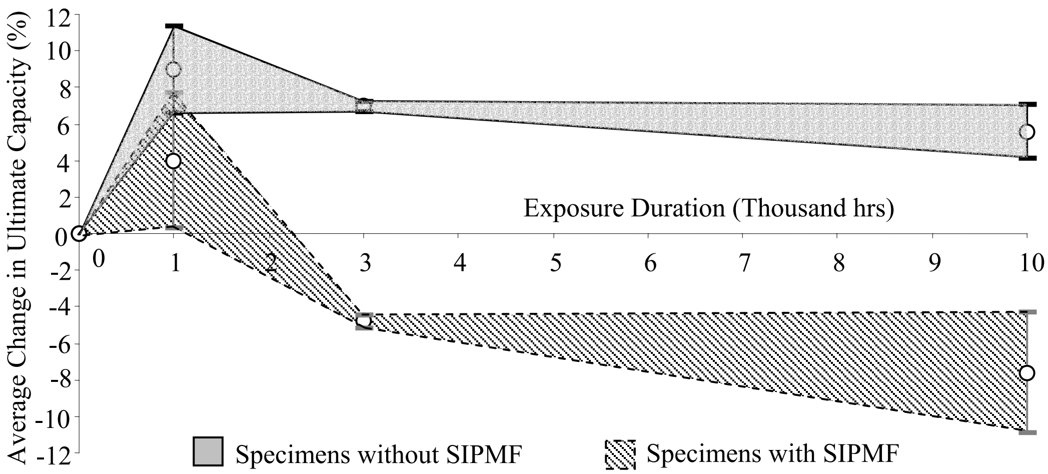


Figure 5.109. Percentage of change in ultimate load carrying capacity for salt-water exposures specimens with and without SIPMF

Table 5.12. Rates of change of ultimate load for salt-water exposure specimens with and without SIPMF

Salt-Water Exposure period	**Rate of Change of Ultimate Load** (% change / 1,000 hours)	
	SIPMF	**No SIPMF**
0 to 1,000 hours	+ 4.0	+ 9.0
1,000 to 3,000 hours	- 4.4	- 1.0
3,000 to 10,000 hours	- 0.4	- 0.2

5.5.3 Correlation between Ultrasonic and Structural Test Results

A strong correlation between trends in ultimate load and average pulse velocity was not observed in the test program. For specimens subjected to environmental exposure, a decrease in ultimate load capacity is observed for the majority of specimens whereas an increase in average pulse velocity was observed for the majority of specimens. The overall increase in pulse velocity after environmental exposure is attributed to extended curing duration and improved hydration conditions in the presence of frequent wetting of the specimens. Despite the apparent increase in the quality of concrete, a decrease in ultimate load is observed for these same specimens. The decrease in ultimate load is attributed to presence of macrofeatures such as cracks that would influence large-scale structural behavior (i.e., ultimate load), but not influence the majority of discrete ultrasonic measurements over the cross section.

CHAPTER 6 : FIELD IMPLEMENTATION

6.1 INTRODUCTION

The ultrasonic inspection methods developed and used in this test program can be implemented for field inspection. Both the through-transmission technique and pulse-echo technique can be used for normal field inspection. The equipment and software needed to implement these methods in the field are described in this chapter.

6.2 THROUGH-TRANSMISSION TECHNIQUE

The through-transmission ultrasonic test method provides for assessment of pulse velocity through the depth of concrete bridge decks. Ultrasonic through-transmission tests conducted on slices of full-depth cores provide a profile of pulse velocity. The hardware required for this method is described in chapter 4. The software required to identify the first arrival time is presented in Appendix B. First arrival time is used to identify travel time for the waveform. Thickness of the slice can be measured using a micrometer. The quotient of thickness to travel time is defined as pulse velocity. The pulse velocity can be related to the quality of concrete using empirical relationships (Krautkramer and Krautkramer 1990). The methodology for determining the Quality Index (*QI*) for a core is presented in Chapter 4. The distribution of pulse-velocity with depth as well as the *QI* for cores can be used for determining the influence of the presence of SIPMFs.

6.3 PULSE-ECHO TECHNIQUE

The method developed for analyzing the contact between SIPMFs and concrete can be adopted for field use. The method for field implementation is demonstrated below:

1) The hardware used for the laboratory experiments is directly transferable to field use. Detailed specifications for the transducer, delay line, and pulser-receiver are presented in Chapter 4. Detailed plans for construction of a transducer holder that provides a repeatable load application (identical to what was used in the laboratory test program) is presented in Figures 6.1 to 6.6. The addition of an extension rod to the transducer holder or an automated track mounting

system to the underside of the bridge deck slab may provide added flexibility for field implementation. A longer cable and a power source (generator) would be required for field implementation.

2) The software used for analysis of laboratory test results is directly transferable to field use. The area confined by the waveform curve is calculated using the trapezoidal method. Threshold values for area confined by the curves are presented for idealized (and controlled) conditions in the laboratory in Chapter 4.

3) The sampling grid used for the laboratory test program is presented in Figure 6.7. Random sampling locations on the underside of the SIPMF can be used in the field to provide statistically representative results. Distribution of sampling locations across the profile of the section should be maintained for selection of measurement locations (columns A through K, Figure 6.7). The number of samples required to achieve representative results was determined using statistical analysis on the results from the laboratory test program. The following steps were used to produce a chart that can be used to identify a suitable number of measurement points for field bridge deck inspection:

a) The finely spaced grid used for the laboratory tests (704 measurement locations) was assumed to provide statistically representative results for defining the percentage of total area classified as good, fair, and poor contact. Therefore, the results from each specimen can be considered statistically "true" in that they provide a valid determination of percentages of area classified as good, fair, and poor contact. In addition, it was assumed that the large-scale laboratory samples provided representative results for assessment of contact. Therefore, equivalency of large-scale laboratory specimens and full-size bridge decks is assumed.

b) Random sampling locations are assumed to be representative for measurement locations. The non-biased spatial distribution of contact quality regions (good, fair, and poor) for laboratory results supports this premise.

c) The results determined in the laboratory investigation for full data sets (704 measurement points) were compared to results from subsets of selected measurement locations from varying numbers of random sampling points on the same specimen. The percentages of areas corresponding to good, fair, and poor contact were determined for the subset of data points. The difference for each category (good, fair, and poor contact) between the true values (as determined using 704 points) and the given number of measurement points was calculated. A plot was produced representing the percentage difference for each category (good, fair, and poor) from true value versus the number of random measurement points (Figure 6.8).

d) The plot presented in Figure 6.8 was constructed to provide determination of the required number of measurements to adequately represent spatial distribution of quality of contact between SIPMF and concrete. A higher number of measurement locations allows for higher precision in determining the percentage of points corresponding to the various degrees of quality of contact between the concrete and the SIPMF. An envelope is presented in Figure 6.8 that contains the great majority of laboratory test data (several outlying datapoints are outside the envelope). The envelope in Figure 6.8 can be used to directly determine (either graphically or by using the equation in Figure 6.8) the minimum number of measurement locations to achieve a given degree of precision in establishing the regions of varying degrees of contact.

4) Timing of measurements in the field relates to the perceived importance of good contact between the SIPMF and the concrete as discussed in Chapter 4. Measurements may be taken shortly following construction to provide baseline values and allow for an assessment of any change occurring over the service life of the bridge deck. Measurements can be taken at any time during the service life of a bridge deck and the after-construction baseline values are not required for interpretation of the results. Assessment of quality of contact over time would require repeated measurements to be taken. Since statistically representative results are achieved using random sampling locations, it is not necessary that sampling locations be the same between various surveys. A series of ultrasonic pulse-echo measurements could be incorporated into a normal bridge deck inspection routine.

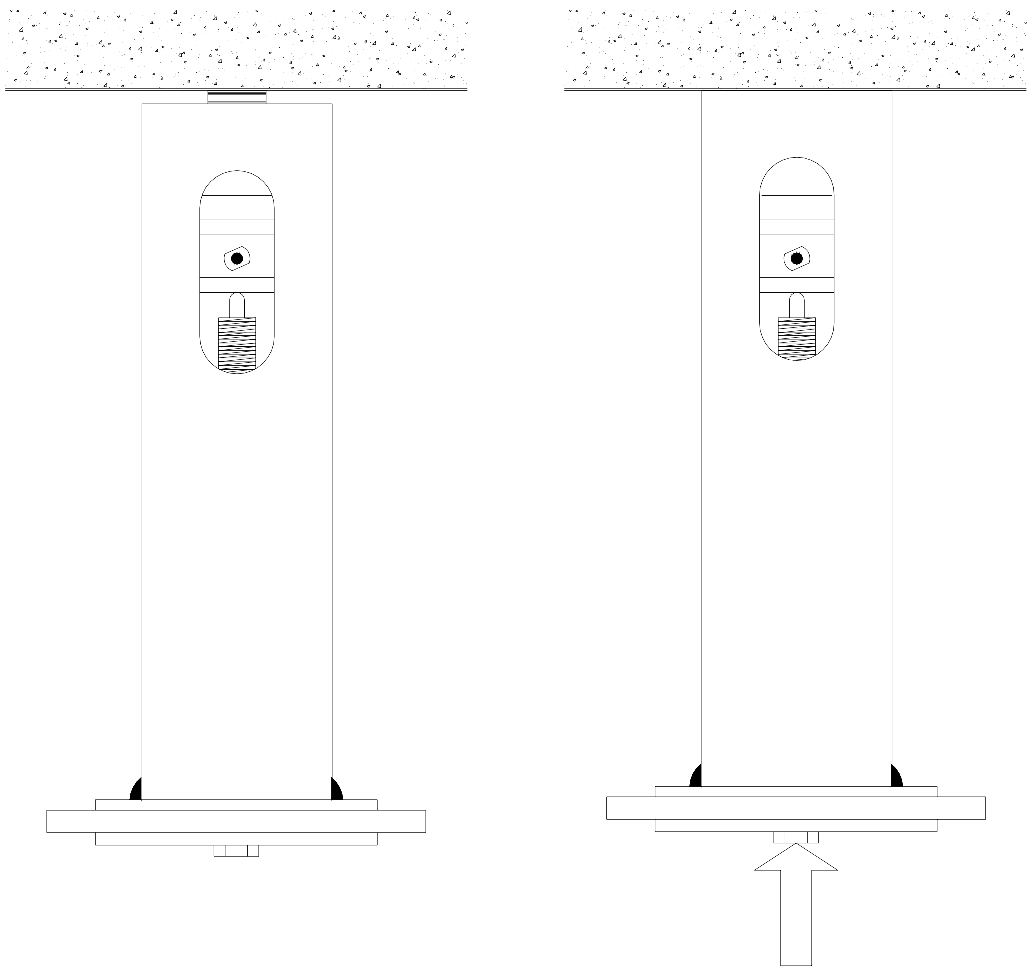


Figure 6.1. Application of transducer for pulse-echo testing using transducer holder

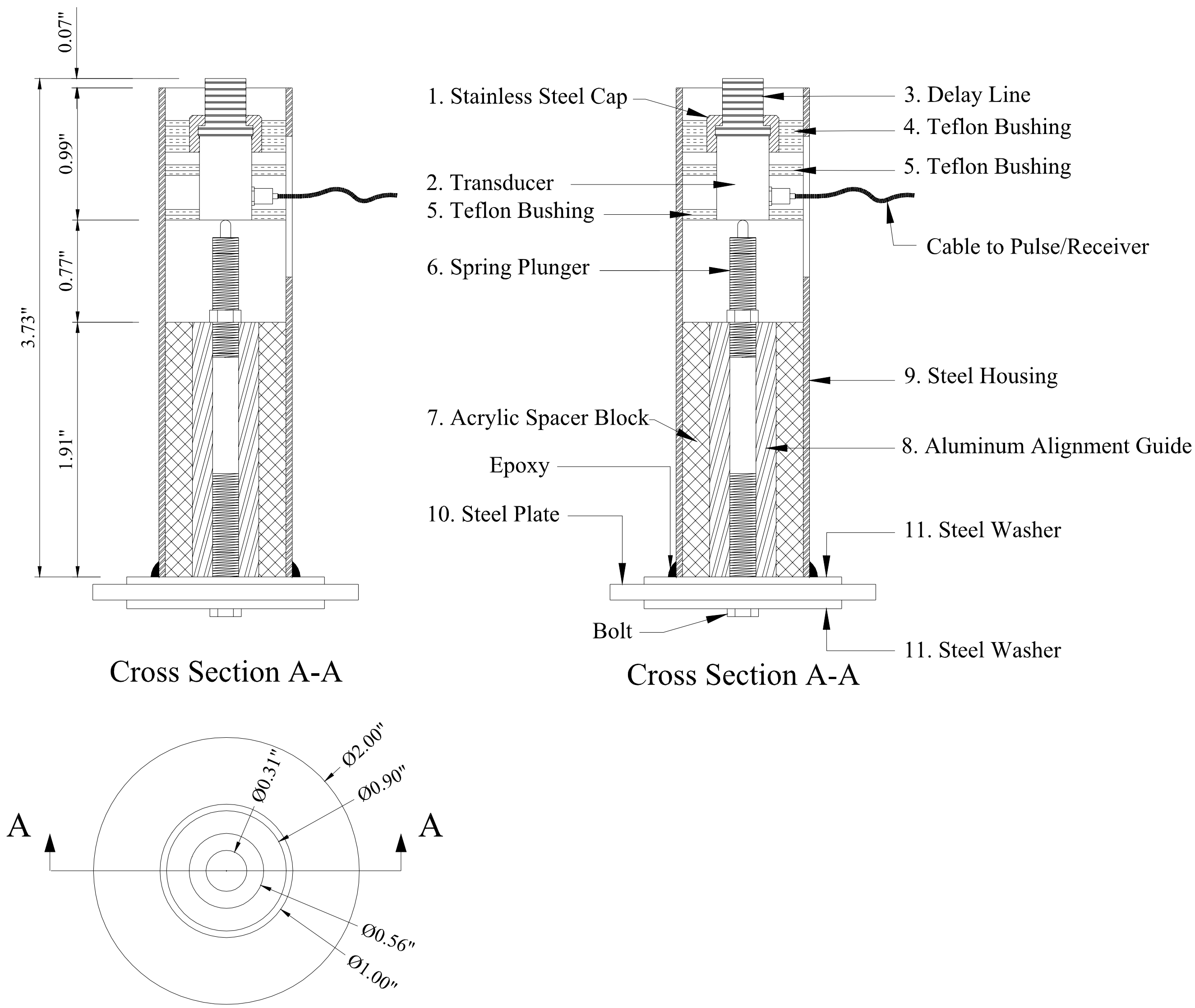


Figure 6.2. Transducer holder details

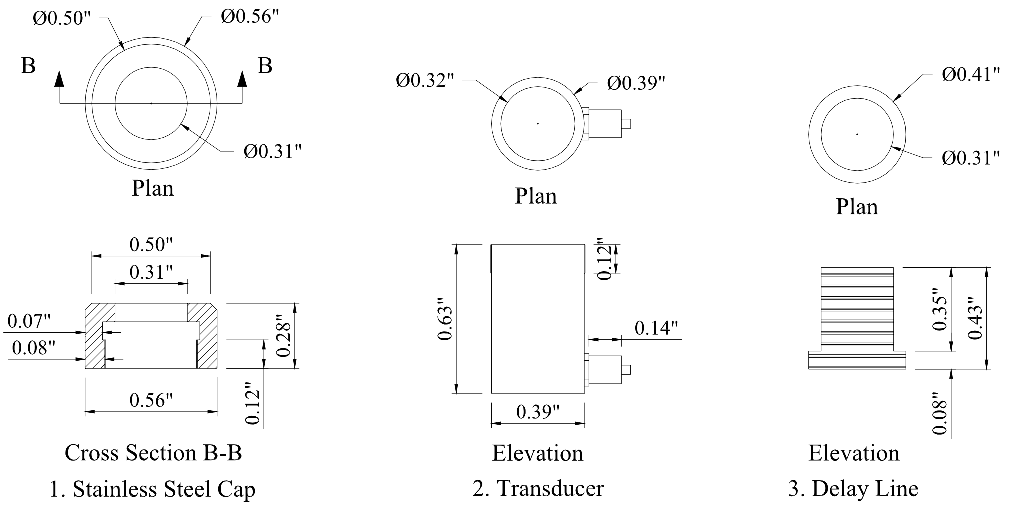


Figure 6.3. Transducer and delay line details

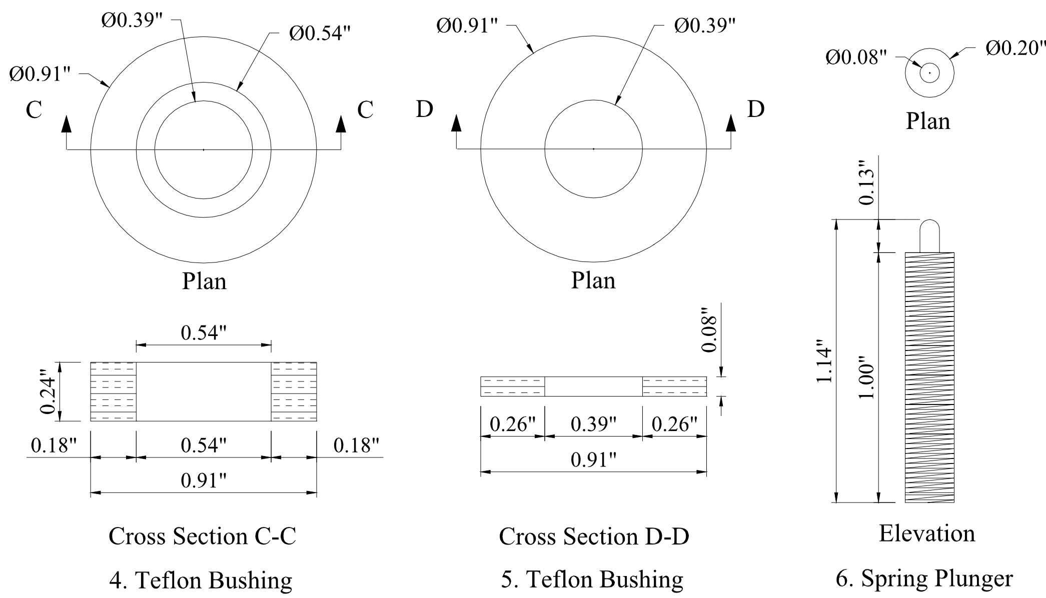


Figure 6.4. Teflon bushing and spring plunger details

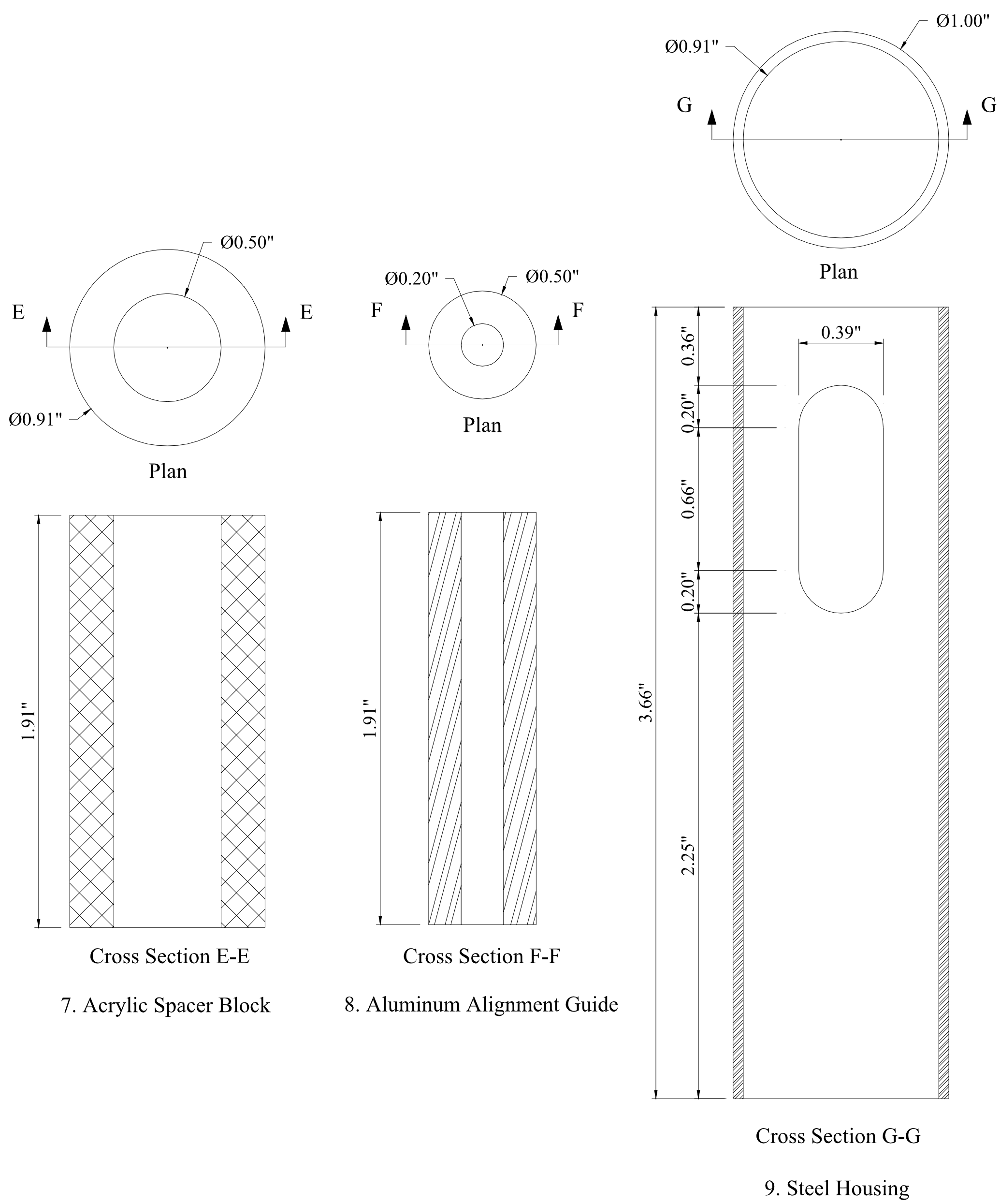


Figure 6.5. Spacer block, alignment guide, and housing details

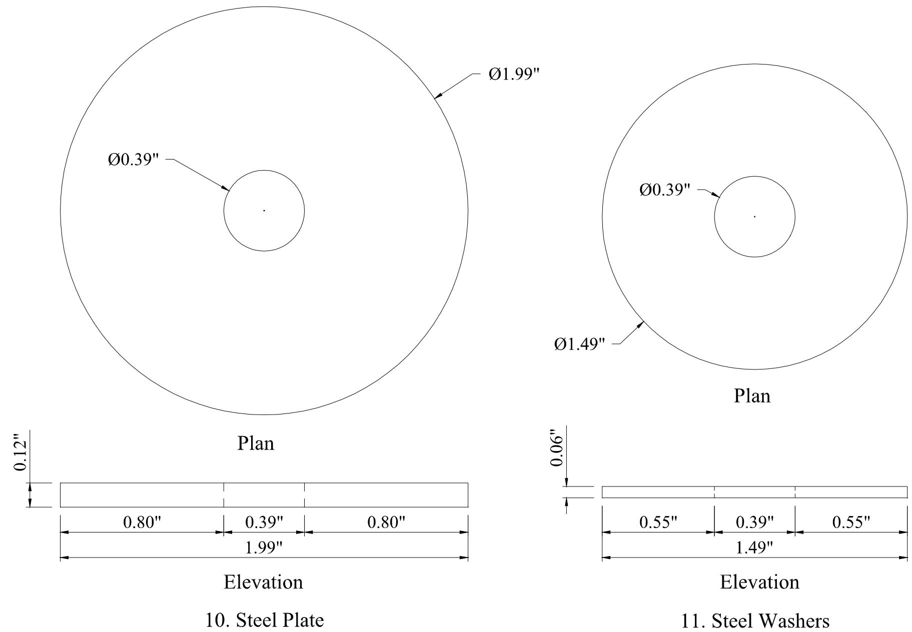


Figure 6.6. Transducer holder base details

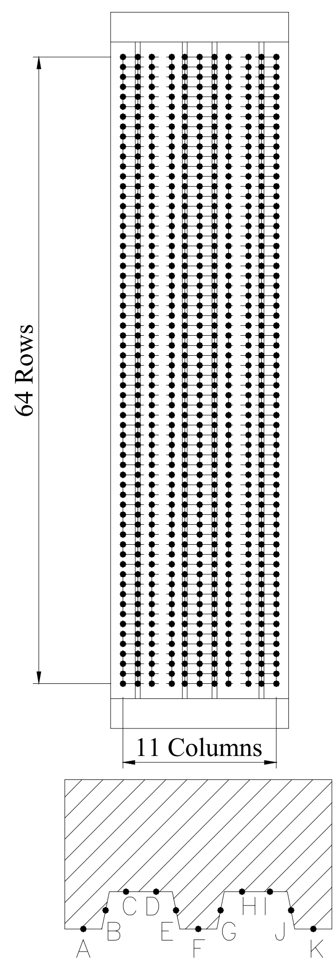


Fig 6.7. Measurement locations for laboratory test specimens

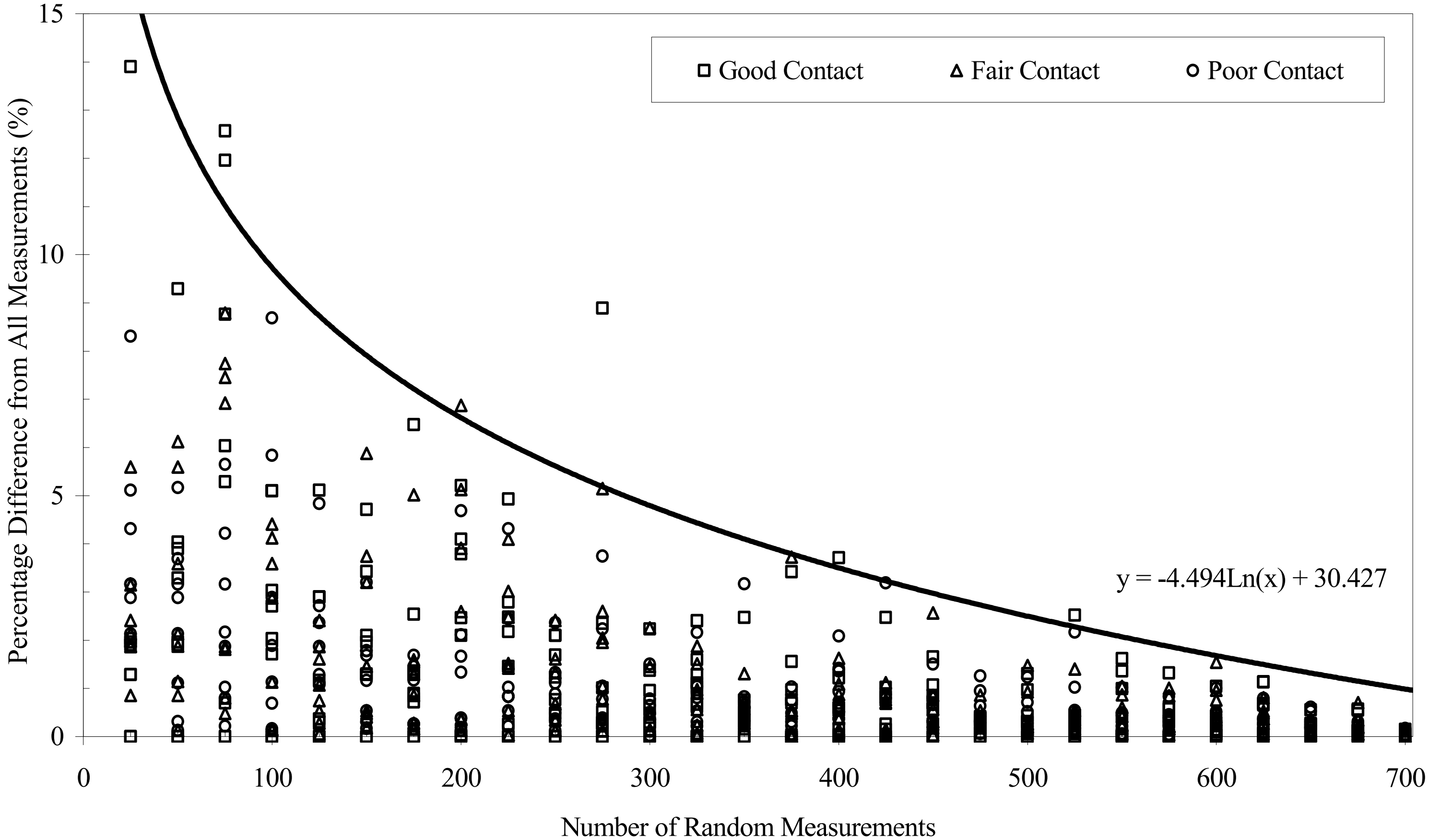


Figure 6.8. Statistical determination of number of measurement points

6.4 SUITABILITY OF FIELD IMPLEMENTATION

The two inspection and evaluation methods used in this research program are both suitable for field implementation. A recommendation is made for MDOT to incorporate through-transmission testing of sliced cores into normal field inspection techniques. This method is straightforward and allows for determination of quality of concrete through the entire bridge deck thickness. Comparative analyses can be conducted to evaluate the influence of SIPMFs on bridge deck performance. A lower priority exists for incorporating pulse-echo inspection of the contact between the SIPMF and the concrete. The importance of intimate contact on bridge deck performance is somewhat debatable. High quality contact between SIPMF and concrete is beneficial, as no space exists for excess ponding of water directly beneath the concrete bridge deck. However, high quality contact could be considered detrimental, as this condition would prevent convection of air for potentially drying out the lower region of the concrete bridge deck. Furthermore, the logistics of field inspection using this technique are somewhat complex. Therefore, the through-transmission technique should be considered the priority for the near future.

CHAPTER 7 : SUMMARY AND CONCLUSIONS

A comprehensive research investigation was conducted to evaluate the use of SIPMFs in construction of concrete bridge decks. A survey was developed and administered to all DOTs to examine the state of the practice of using SIPMFs for concrete bridge deck construction. Additionally, a field investigation was conducted to evaluate the performance of existing concrete bridge decks constructed with and without SIPMFs. This field investigation included visual inspection of 10 bridge decks and laboratory investigation of full-depth cores obtained from the inspected bridge decks. The cores were investigated using visual inspection, compressive strength tests, and ultrasonic tests. The compressive strength tests provided overall strength for the concrete used in the inspected bridges. The ultrasonic tests provided means for evaluating the quality of concrete through the depth of bridge deck. A laboratory durability investigation was conducted on 24 large-scale bridge deck slab specimens with and without SIPMF. Four specimens were used as control specimens, and the remaining 20 specimens were subjected to either freeze/thaw exposure and repeated load cycles or salt-water exposure and repeated load cycles. At various stages before, during, and after the environmental exposure, ultrasonic pulse-echo testing was used to determine the quality of contact between the SIPMFs and concrete for specimens with SIPMF. Furthermore, after the completion of the environmental exposure, ultrasonic through-transmission testing was used to assess the condition of the concrete for all specimens. These tests were followed by the ultimate load tests. Conclusions from each phase of the research investigation are outlined below.

Based on the survey responses provided by 39 DOTs, the following conclusions were drawn:

1) Two-thirds of responding DOTs allow the use and one-third of responding DOTs do not allow the use of SIPMFs in concrete bridge deck construction. Most of the DOTs that use SIPMFs are satisfied with the performance of this bridge deck system.
2) The majority of DOTs that do not use SIPMFs are concerned with the inability to visually examine and access the bottom of the deck slabs.
3) The majority of DOTs use conventional inspection approaches such as visual inspection, and hammer sounding for periodic examination of their SIPMF bridge decks.

4) Most of the DOTs do not believe that the SIPMF increases the long-term durability of bridge decks. The majority of DOTs reported that the use of SIPMFs is not linked to any deck deterioration.
5) Statistical bias is present in the data with regard to climatic region. The overall acceptance of use of SIPMFs and satisfaction with performance of SIPMF decks is generally higher for the Southern region compared to the Northern region of the country.
6) By comparing results of the survey to a similar survey administered in 1974, an increase in the overall use of SIPMFs is observed. However, some DOTs remain hesitant to adopt widespread use of SIPMFs for concrete bridge deck construction.

Based on the field inspection and coring of bridge deck slabs, the following conclusions were drawn:

1) From the visual field inspection and visual inspection of cores, it was determined that the two bridge deck systems were similar. Statistical analysis of compressive strength and ultrasonic pulse velocity tests also indicated similarity of the bridge deck systems for all of the decks as well as for direct comparison decks (for which traffic and environmental loads were identical).
2) The ultrasonic test results through the depth of the cores did not indicate specifically beneficial or adverse effects of the presence of SIPMF on the bridge decks.
3) Overall, the performance of concrete bridge decks constructed with SIPMFs was determined to be similar to the performance of concrete bridge decks constructed without SIPMFs.

Based on results of the laboratory structural test program, the following conclusions were drawn:

1) The average compressive strength of the cylinders that were cured under controlled conditions increased for curing periods up to 28 days, and decreased slightly for further curing times. The average compressive strength of the cylinders decreased with freeze/thaw exposure, and several cylinders deteriorated entirely. The average compressive strength of the cylinders for salt-water exposure increased with increasing time of exposure.

2) Generally, a reduction in the ultimate load carrying capacity was observed for all freeze/thaw specimens with and without SIPMFs except for specimen WO-F-3-2. After 300 cycles of freeze/thaw exposure, greater reduction in the ultimate load carrying capacity was observed for specimens with SIPMF than for specimens without SIPMF (approximately 5%). After further freeze/thaw exposure (600 total cycles), similar reduction in the ultimate load carrying capacity for all specimens with and without SIPMF was observed. This reduction was attributed to the deterioration of specimens with and without SIPMF due to freeze/thaw exposure.
3) An initial increase in ultimate load carrying capacity was observed after 1,000 hours of salt-water exposure for specimens with and without SIPMF. For further salt-water exposure, a relative decrease in ultimate load was obsereved for specimens with and without SIPMF. A larger decrease in ultimate load between 1,000 and 3,000 hours of salt-water exposure was observed for specimens with SIPMF than specimens without SIPMF. The average change in ultimate load carrying capacity for specimens with and without SIPMF between 3,000 and 10,000 hours of salt-water exposure was not significant. After 10,000 hours of salt-water exposure, the ultimate loads for specimens with SIPMF were less than baseline values, whereas ultimate loads for specimens without SIPMF were greater than baseline values.

Based on the ultrasonic pulse-echo tests on laboratory specimens the following conclusions were drawn:

1) The regions of consistent contact rating (good, fair, and poor) were generally well distributed over the entire area of SIPMF.
2) The overall trend of quality of contact between SIPMF and concrete was generally consistent for all freeze/thaw exposure specimens. The initial contact (before cracking) was consistently good, whereas a significant loss of contact occurred upon service load cracking. Essentially all contact was lost after 300 freeze/thaw cycles, and an apparent improvement of contact was observed after 600 freeze/thaw cycles. The apparent improvement in contact was attributed to accumulation of mineral precipitate between the SIPMF and concrete, which was traced to concrete/cement origin.

3) A similar trend of quality of contact between SIPMF and concrete was generally observed for all salt-water exposure specimens. The initial contact (before cracking) was consistently good, a significant loss of contact occurred upon service load cracking, and an apparent improvement of contact was observed with continued salt-water exposure (1,000, 3000, and 10,000 hours of salt-water exposure). The apparent improvement in contact was attributed to accumulation of mineral precipitate on the top and bottom surfaces of the SIPMF, which was traced to cement and salt origin.

Based on the ultrasonic through-transmission tests on laboratory specimens the following conclusions were drawn:

1) With the exception of generally lower pulse-velocities in regions containing cracks, the pulse-velocities were generally well distributed over the entire longitudinal cross section of the specimens. Average pulse-velocity for perimeter, interior, bottom, and total regions were generally similar.
2) An increase in the average pulse-velocity was observed for all freeze/thaw specimens with and without SIPMFs compared to the average pulse-velocity of the respective control specimens with and without SIPMFs. For specimens without SIPMFs, a continual increase in pulse-velocity was observed for freeze/thaw exposure. For specimens with SIPMFs, an increase in pulse-velocity was observed after 300 freeze/thaw cycles. A decreasing trend of pulse-velocity was observed for specimens with SIPMFs after further freeze/thaw exposure (600 total cycles), although the average pulse-velocity remained greater than the average control pulse-velocity (approximately 6%).
3) Relatively small changes in pulse-velocity were observed in response to salt-water exposure. Measured average pulse-velocities after 1,000 hours of salt-water exposure were close to values determined using control specimens. In all cases, the average pulse-velocity increased with further duration of salt-water exposure (3,000 and 10,000 hours total exposure). After 10,000 hours of salt-water exposure, the average pulse-velocity for specimens with SIPMF was higher than the average pulse-velocity for specimens without SIPMF (approximately 3%).

Overall, apparent equivalency of deck performance was observed using field inspection, visual inspection of cores, compressive strength of cores, and pulse-velocity profile of the cores. Small changes in the performance of bridge deck specimens with and without SIPMFs were measured during the structural and ultrasonic laboratory test programs.

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APPENDIX A: SURVEY REPORT

Survey on the Performance and Inspection Techniques for Bridge Decks Constructed with Stay-in-place-Metal-Forms

Report submitted to
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June 26, 2002

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Survey on the Performance and Inspection Techniques for Bridge Decks Constructed with Stay-in-Place Metal Forms

Introduction:

In December 2001, the Michigan Department of Transportation (MDOT) awarded the Structural Testing Center at Lawrence Technological University of Southfield, Michigan, a research contract to investigate the use of stay-in-place metal forms (SIPMFs) in bridge deck slabs. This research included the investigation of inspection procedures and deterioration modes of this type of bridge deck. One of the major tasks of this investigation was to conduct a nationwide survey on the performance and inspection techniques for bridge decks constructed with SIPMF. A comprehensive survey was developed, approved by MDOT Engineers, and delivered via e-mail to all fifty-two DOTs. A total of 38 DOTs responded to the survey. These DOTs are: Alabama, Alaska, Arizona, Arkansas, California, Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Illinois, Iowa, Kansas, Kentucky, Maine, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, Ohio, Oklahoma, Oregon, Tennessee, Texas, Washington, West Virginia, Wyoming, and Virginia. This report summarizes the findings of this survey. The responses from the 38 DOTs are summarized and presented in this report along with the survey.

Survey:

The survey consisted of a variety of questions that were tailored to address the following issues:

1. The policy of various states on the use of SIPMF.
2. Reasons for not allowing the use of SIPMF.
3. Number and status of bridge decks constructed with SIPMF.
4. The age of available SIPMF bridge decks.
5. Satisfaction of the performance of SIPMF.
6. Use of filling material (Styrofoam) in SIPMF corrugations.
7. Use of epoxy-coated reinforcement with SIPMF.
8. Methods and interval periods of inspection.
9. Types and causes of deterioration of deck slabs and corrosion of SIPMF.
10. Effect of joint leakage on SIPMF.

A copy of the survey is included in Appendix A.

Discussion of DOT Responses:

The responses from the 38 DOTs were analyzed and presented in Figures 1-25. The number assigned to each figure matches the number assigned to the questions listed in the survey. Also, the title given to each figure is taken from the questions that were listed in the survey. It should be pointed out that the discussion and conclusions drawn from this survey pertain only to the DOTs that responded.

Examination of Figures 1-3 indicates that 26 states allow and 12 states do not allow the use of SIPMF. This policy may be attributed to the weather and the environmental conditions of the location of each state. Furthermore, Figure 3 suggests that the main reason that some states don't allow the use of SIPMF is that the presence of SIPMF may interfere with the inspection of bridge decks. Another reason cited by DOTs for not allowing the use of SIPMF is its susceptibility to potential corrosion problems due to the trapped water and salt between the forms and concrete. Also, it was indicated that Florida DOT doesn't allow the use of the SIPMF on bridges crossing over water.

As presented in Figure 4, only five states have more than 1000 bridges constructed with SIPMF, 3 states have between 500 and 1000 bridges, 8 states have between 100 and 500 bridges, and 15 states have less than 100 bridges. This suggests that SIPMF bridge decks are not commonly used in a majority of the bridges in each state. Only 11 states, including Alaska, Arizona, Alabama, California, Connecticut, Georgia, Idaho, Michigan, New York, Tennessee, and Virginia, have been using this type of bridge deck for more than 30 years, as presented in Figure 5. However, it should be pointed out that some of these states, such as Alaska, Arizona, California, Connecticut, and Idaho, each have less than 100 bridges of this type (Figure 4).

The level of satisfaction with the performance of this type of bridge deck is presented in Figure 6. The majority of the DOTs are satisfied with various levels. Four states are very satisfied, 10 states are satisfied and 15 states are neutral with regard to satisfaction. OHDOT is only DOT that is very dissatisfied and CTDOT is not satisfied with the SIPMF performance. Apparently, most of the very satisfied and satisfied DOTs are in the southern states. This suggests that level of satisfaction is dependent on the climatic and environmental conditions of each state.

Out of the 29 DOTs that use SIPMF, 20 DOTs do not fill the corrugations of the forms with Styrofoam to reduce the dead load, as presented in Figure 7. Only 6 DOTs indicated that they do fill the corrugations with Styrofoam and the remaining 3 DOTs sometimes fill the corrugations. This suggests that filling the corrugations of the forms is not a common practice in most of the states that use SIPMF.

An assessment of the use of epoxy-coated steel bars with SIPMF in this type of bridge deck is presented in Figure 8. From the 28 DOTs that responded to this question, 25 DOTs use epoxy-coated steel bars and only 3 DOTs do not use epoxy-coated steel bars. Only 4 DOTs reported a difference in performance between decks with SIPMF constructed with black steel bars and those constructed with epoxy-coated steel reinforcement (Figure 14).

The various reported methods of inspection for SIPMF deck slabs are presented in Figure 9. Only 5 DOTs use inspection methods other than the traditional visual inspection and hammer sounding of the surface. These methods include chain-drag, form-cut-out, full-depth coring, and mapping cracks. It is evident that there is no nondestructive inspection approach used for inspection for this type of bridge deck. Perhaps that explains the reason for the lack of gathering adequate and specific data related to the SIPMF bridge deck slabs (Figure 10). This lack of gathering adequate information may be attributed to the lack of the widespread use of the SIPMF for bridge construction in all states. The period between each inspection of decks is generally from 1 to 3 years, as shown in Figure 11.

Figure 12 presents the status of existing SIPMF decks in different areas of the country. Four DOTs reported that their bridges are in excellent conditions and 15 DOTs indicated that their bridges are in good condition. Examining this Figure suggests that most of these 19 DOTs are in the southern states. However, 7 DOTs, most of them are in northern states, reported that their bridges are in fair condition. Climatic and environmental conditions are likely the major contributing factors for the deterioration. It should be pointed out that the majority of the DOTs do not believe that the use of SIPMF increases the long-term durability of bridge decks. Only NMDOT and NJDOT believe that the SIPMF increases the durability of bridge decks, as shown in Figure 13.

The types of and extent of both deterioration and corrosion of this type of bridge deck are shown in Figures 15 and 18, respectively. Fifteen DOTs reported no deterioration in their bridges, whereas 4 DOTs reported corrosion in the forms (Figures 15). IDDOT indicated that they have light rusting between the overlap of the SIPMF, and rusting of SIPMF due to the trapping of moisture between the forms and the deck. TXDOT stated that they have some of the SIPMF corroded but with no deterioration in the deck that can be related to the use of SIPMF. Also, NYDOT reported rusting in the forms. ORDOT reported that they have pop-outs in the forms. Michigan is the only state that reported that their bridges have concrete cracking directly related to the orientation of the angle used for attaching the forms to the beams.

The majority of the DOTs acknowledged that the causes of this deterioration are unknown (Figure 16). However, IDDOT and ORDOT reported that the surface loads are the cause of deterioration. Furthermore, Idaho and New York DOTs reported that environmental conditions are the causes of deterioration. Transverse cracking is the most common type of cracking in this type of bridge deck (Figure 17). In general, 12 DOTs observed corrosion and 14 DOTs observed no corrosion in the SIPMF (Figure 18). Examination of Figure 19 suggests that the locations of most extensive corrosion in the SIPMF are at areas of water leakage and the joints. These corroded areas are at the ends of the spans, along the fascia girders, drop inlet on bridge decks, joints with sealing materials, and joints without sealing materials.

Figures 20-22 address the extent and location of corrosion of the deck reinforcements. Eighteen DOTs observed no corrosion and 6 states observed corrosion in the deck reinforcements, as shown in Figure 20. Figure 21 suggests that the top reinforcements and the span-ends experienced the most extensive concentration of corrosion. This reported extensive corrosion occurred after more than ten years of service (Figure 22).

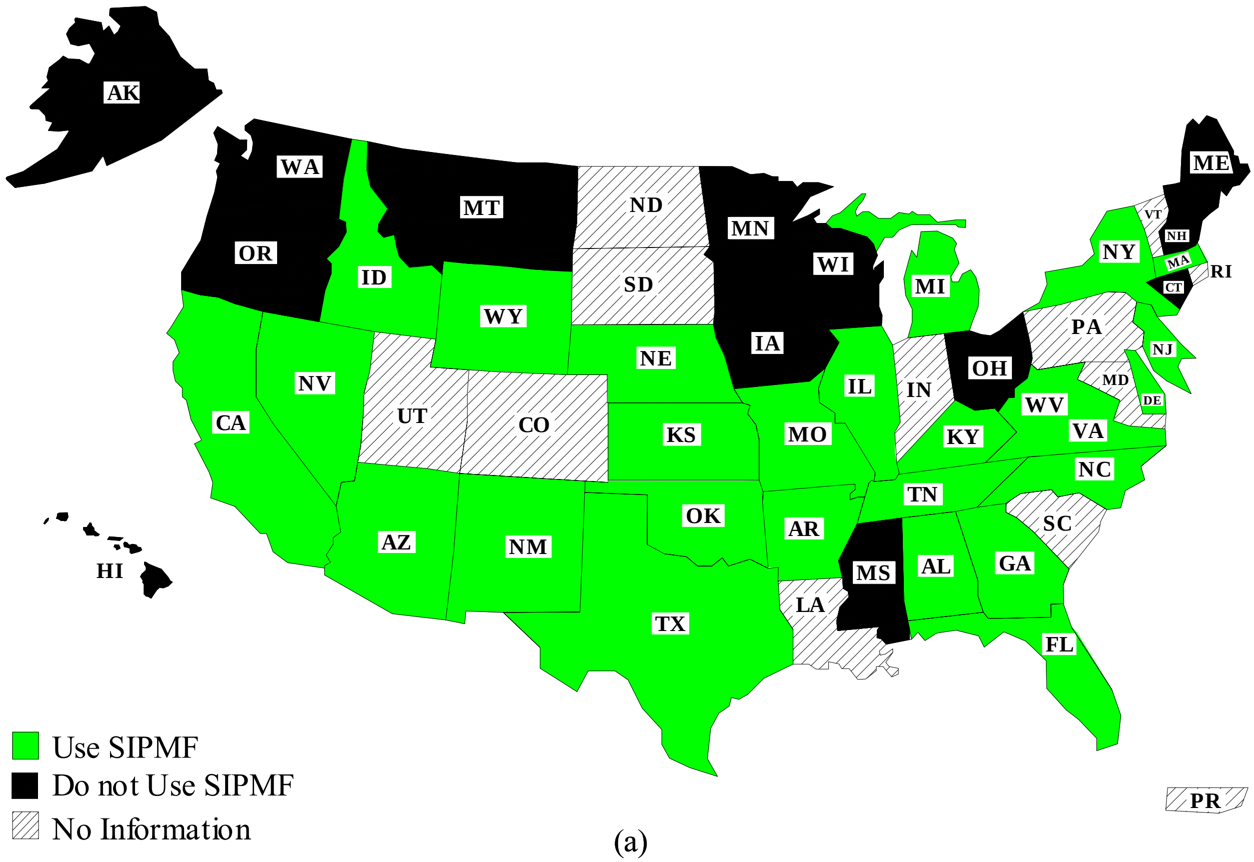
Figure 23 indicates that 6 DOTs in the northern states reported an effect of joint leakage on the SIPMF whereas 17 DOTs in the southern states reported no observation of such leakage effect on the forms. In conclusion, as presented in figure 24, only three DOTs observed problems as a direct result of using SIPMF in bridge decks.

None of the DOTs, with the exception of MIDOT and IADOT, were aware of any research reports in their states related to using SIPMF for bridge deck construction (Figure 25).

Conclusions:

Based on the responses provided by 38 DOTs, the following conclusions can be drawn:

1. A total of 26 DOTs allow the use and 12 DOTs do not allow the use of SIPMF. This policy may be attributed to climatic and environmental conditions in each state. Most of 26 DOTs are satisfied with the performance of this bridge deck system. The majority of DOTs that do not use SIPMF are concerned with the lack of visual examination and accessibility to the bottom of the deck slab.
2. Only five states located on the eastern region of the country have more than 1000 bridges each, whereas 15 states have less than 100 bridges each. Of the remaining states allowing the use of SIPMF, each has between 100 and 1000 SIPMF bridge decks. Eleven DOTs have been using SIPMF for more than 30 years and some of them have reported less than 100 bridges of this type.
3. Filling the corrugations of SIPMF with Styrofoam to reduce the dead weight of bridge decks is not a common practice among the majority of the DOTs that allow their use in bridge decks.
4. The use of epoxy-coated steel bars in bridges with SIPMF is a common practice in most states. The majority of the DOTs did not observe a difference in performance between decks with SIPMF constructed with bare steel reinforcement and those constructed with epoxy-coated steel reinforcement.
5. The majority of the DOTs use conventional inspection approaches such as visual inspection, and hammer sounding for periodic examination of their SIPMF bridge decks. The typical period between each inspection is from 1-3 years. However, none of these DOTs gather specific data related to this type of bridge deck.
6. Most of the DOTs do not believe that the SIPMF increases the long-term durability of bridge decks. The majority of the DOTs reported that the use of SIPMF is not linked to any deck deterioration and the causes of this deterioration are unknown. However, 12 DOTs observed corrosion and 14 DOTs observed no corrosion in the SIPMF. Most of the reported zones of corrosion are located at places of water leakage and joints.
7. Only six DOTs observed corrosion and 18 DOTs observed no corrosion in the deck reinforcement. The reported corrosion is in the top reinforcement and at the span ends.
8. Three DOTs observed problems as a direct result of using SIPMF.
9. There is no significant research work/report available on this type of bridge decks.



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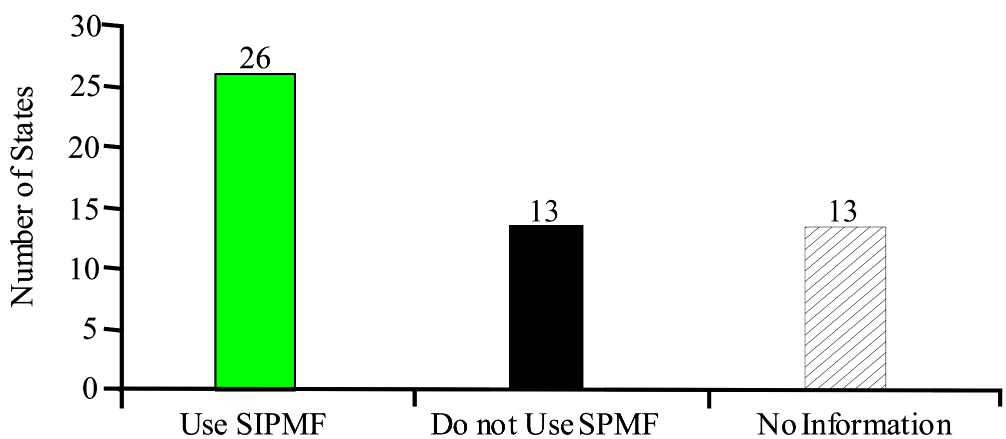

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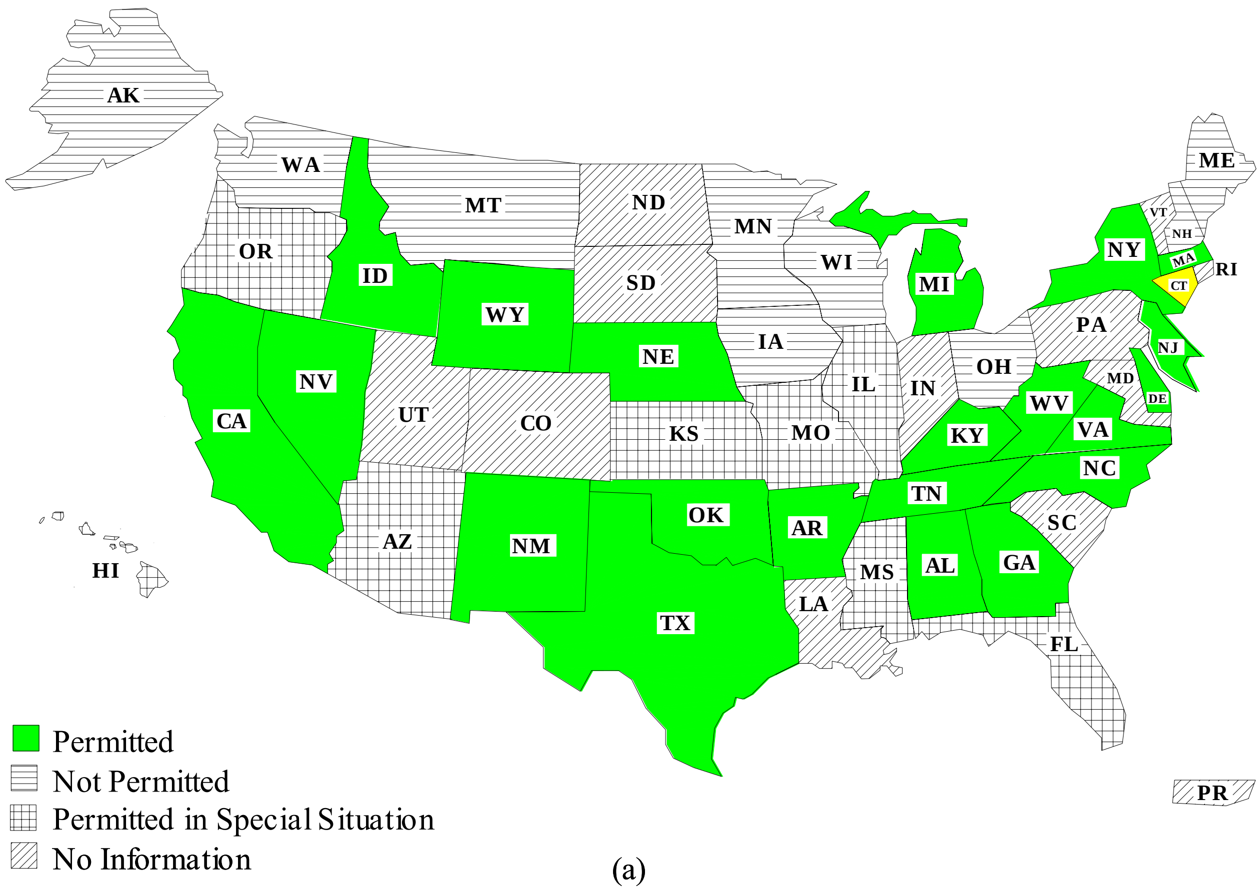
Figure 1. Does your state use SIPMFs for constructing deck slab bridges?



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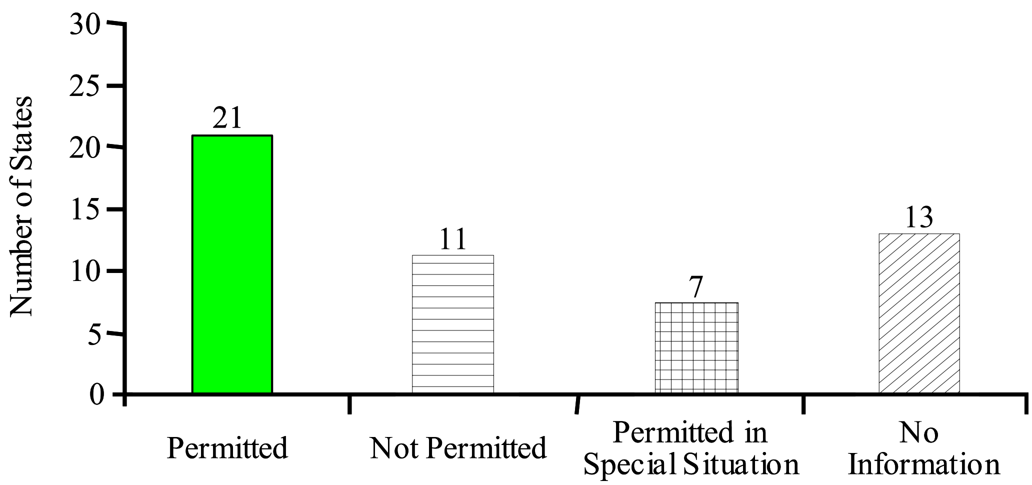

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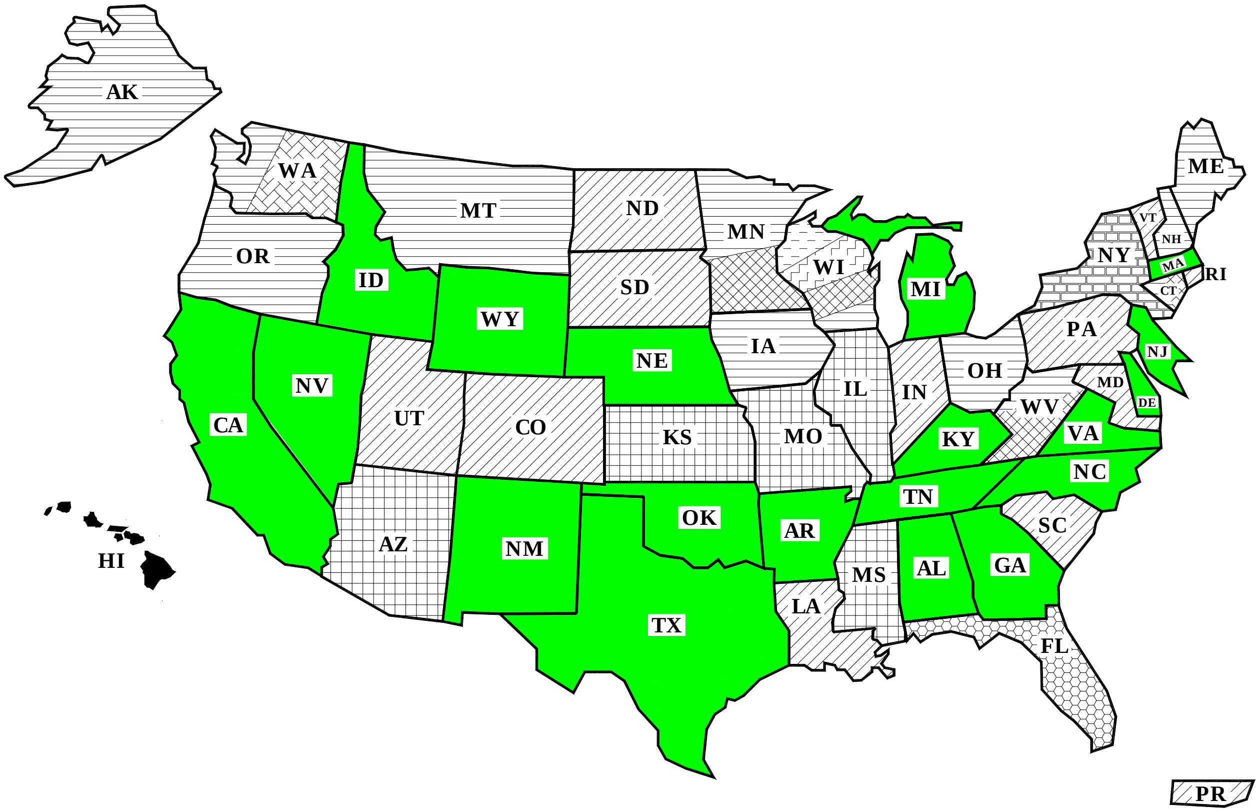
Figure 2. What is your state's policy concerning the use of permanent SIPMF?



(a)

SIPMF interfere with the inspection of bridge decks form underneath (12 states)

Suspect that SIPMF may trap water and salt and so contribute to deck deterioration (4 states)

SIPMF is allowed only on road crossings not on water crossings (Florida)

SIPMF unsightly when they start to corrode (Hawaii)

SIPMF are not allowed at the bays where there is a closure pour (New York)

Corrosion of SIPMF causes staining and objectionable aesthetics (Washington State)

Tack welding to tension flange affects the growth of fatigue crack (Wisconsin)

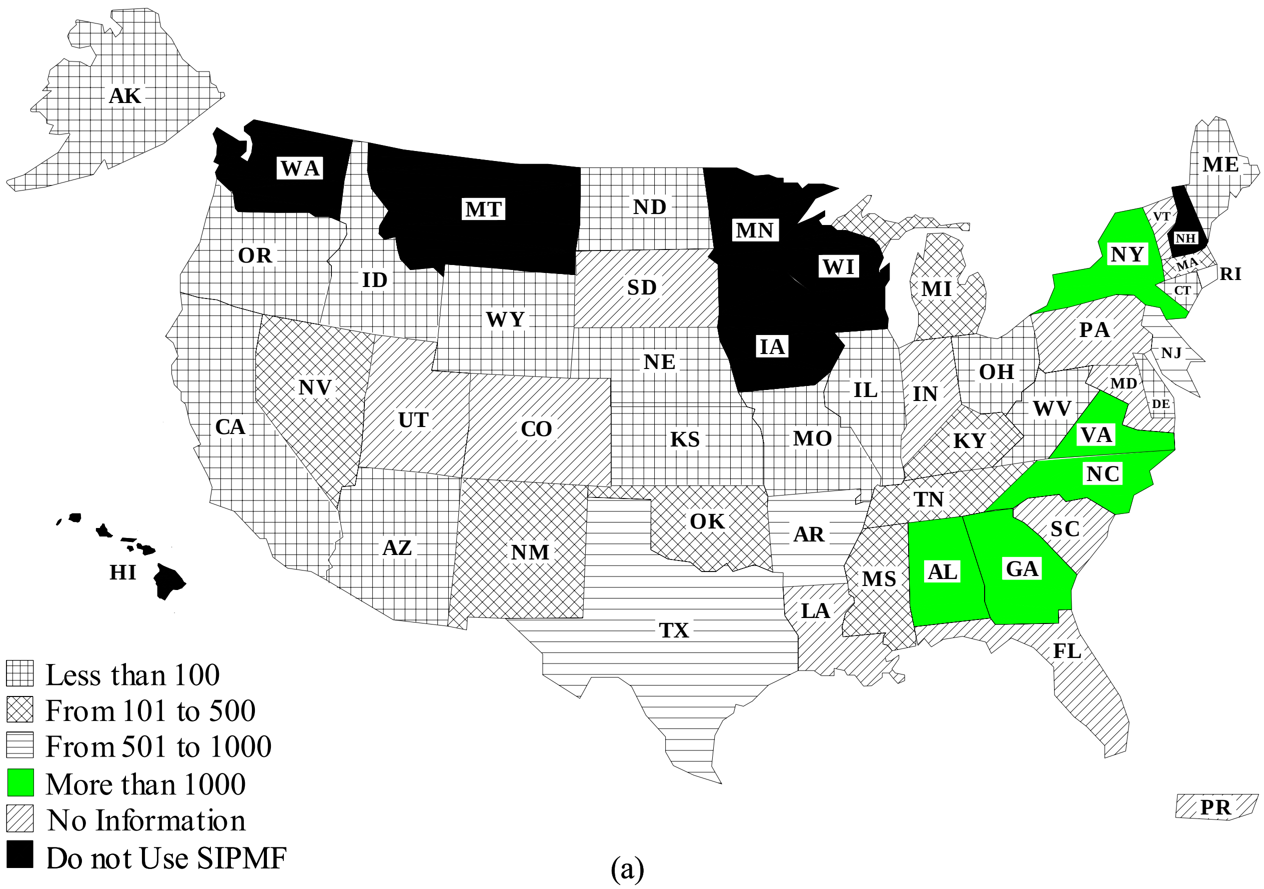
Water runs down the girder flange which causes deterioration to the girder itself (Wisconsin)

Permit the use of SIPMF

Permit the use of SIPMF in special situation

No Information

Figure 3. In the case that your state does not use SIPMF, please specify the reasons.



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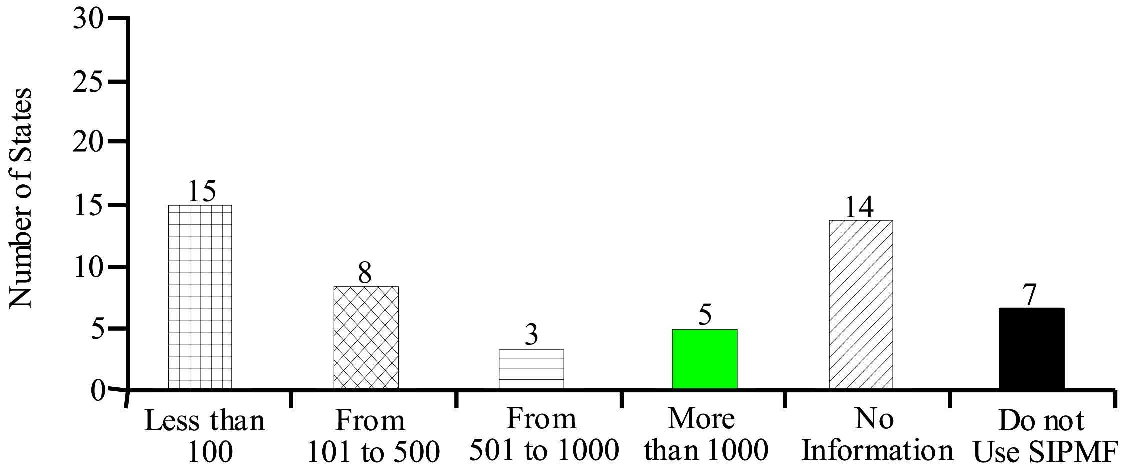

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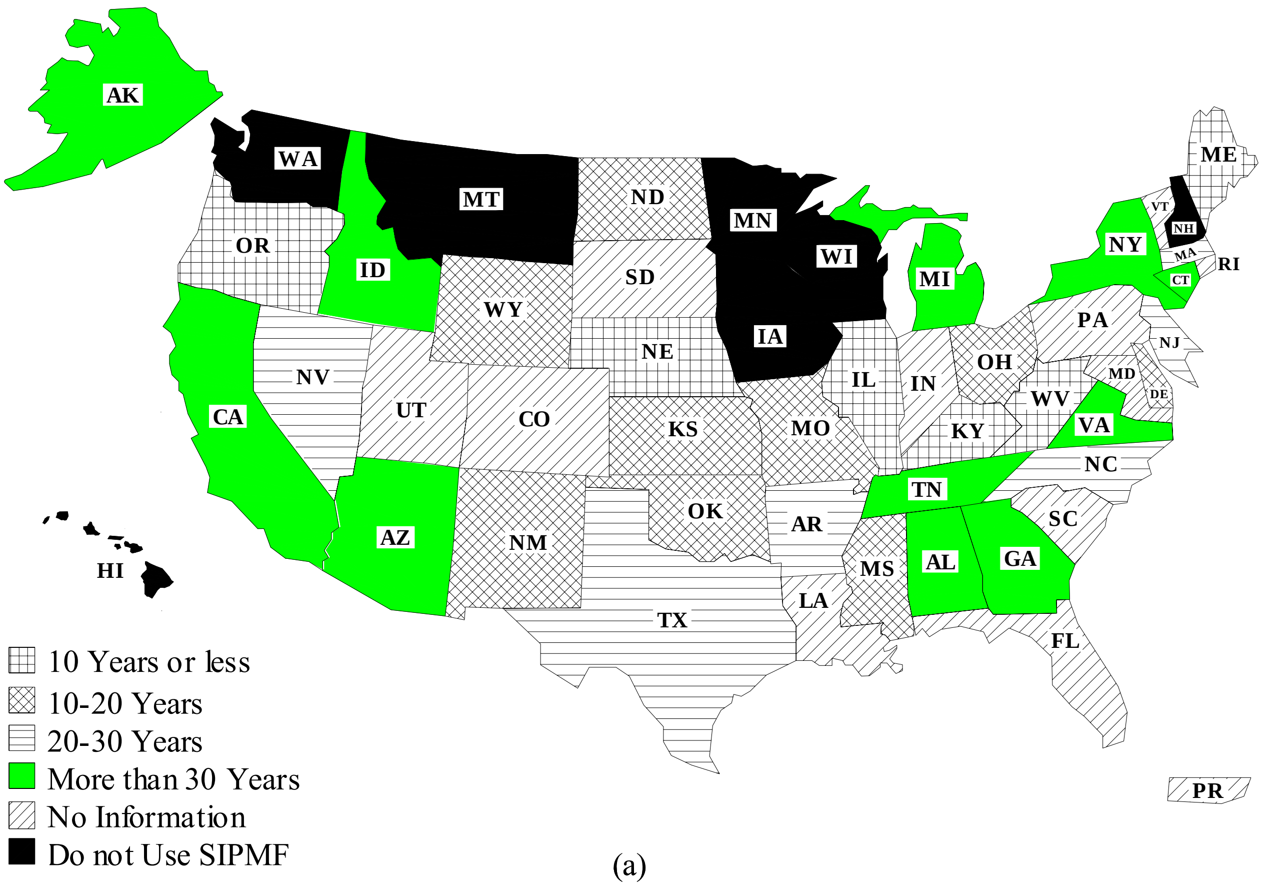
Figure 4. Approximately how many bridges having decks with SIPMF does your state have?



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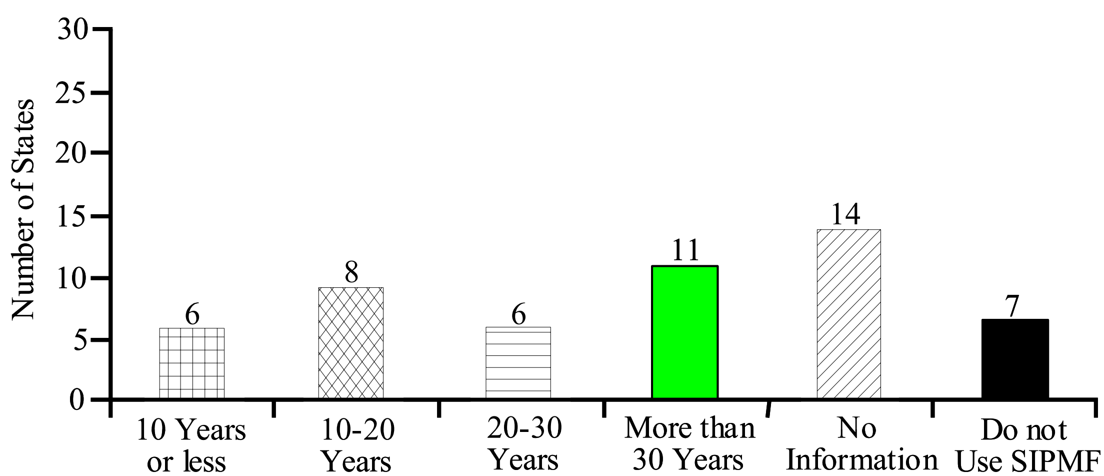
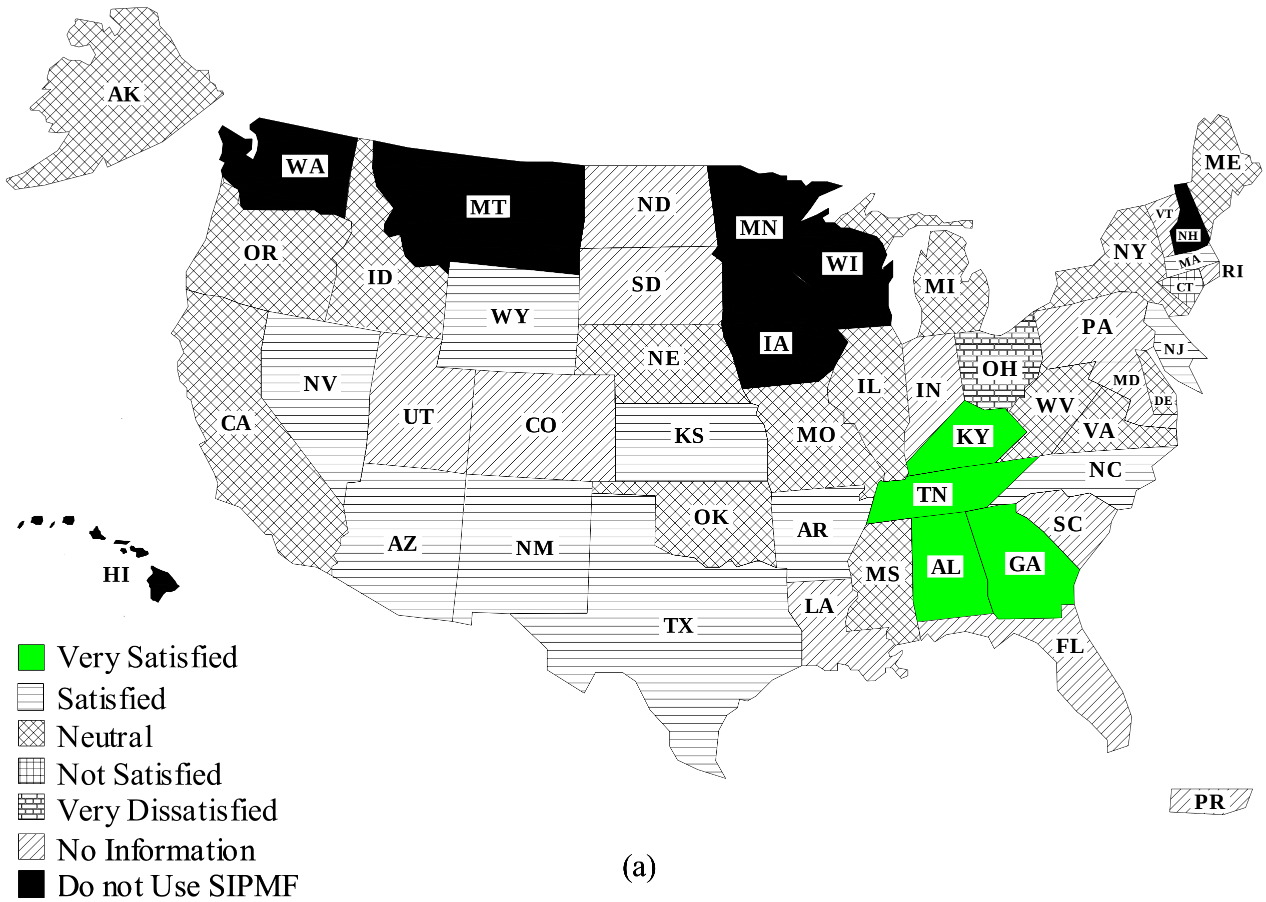


(b)

Figure 5. Approximately how long have decks with SIPMF been used by your state in bridges?



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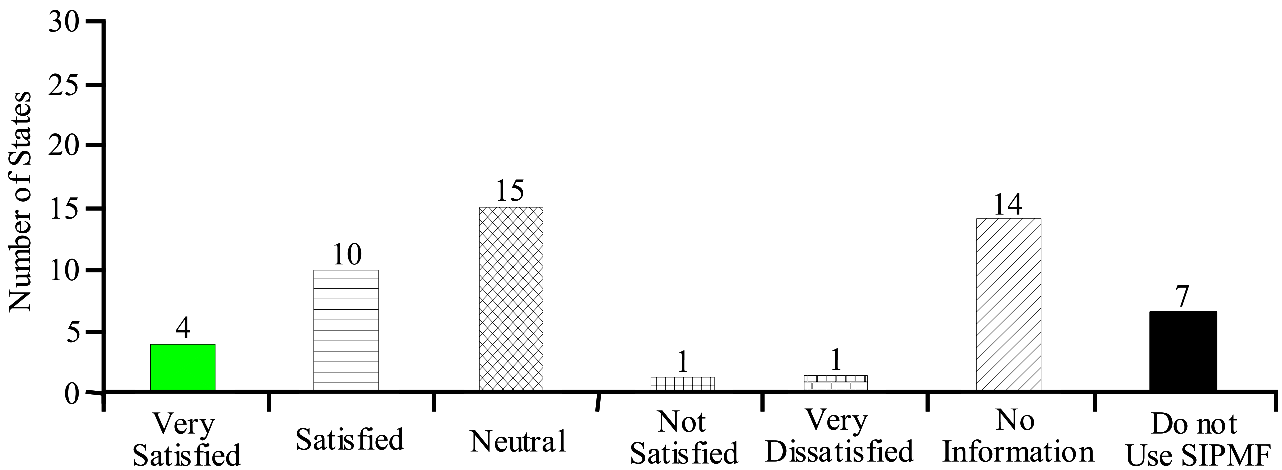

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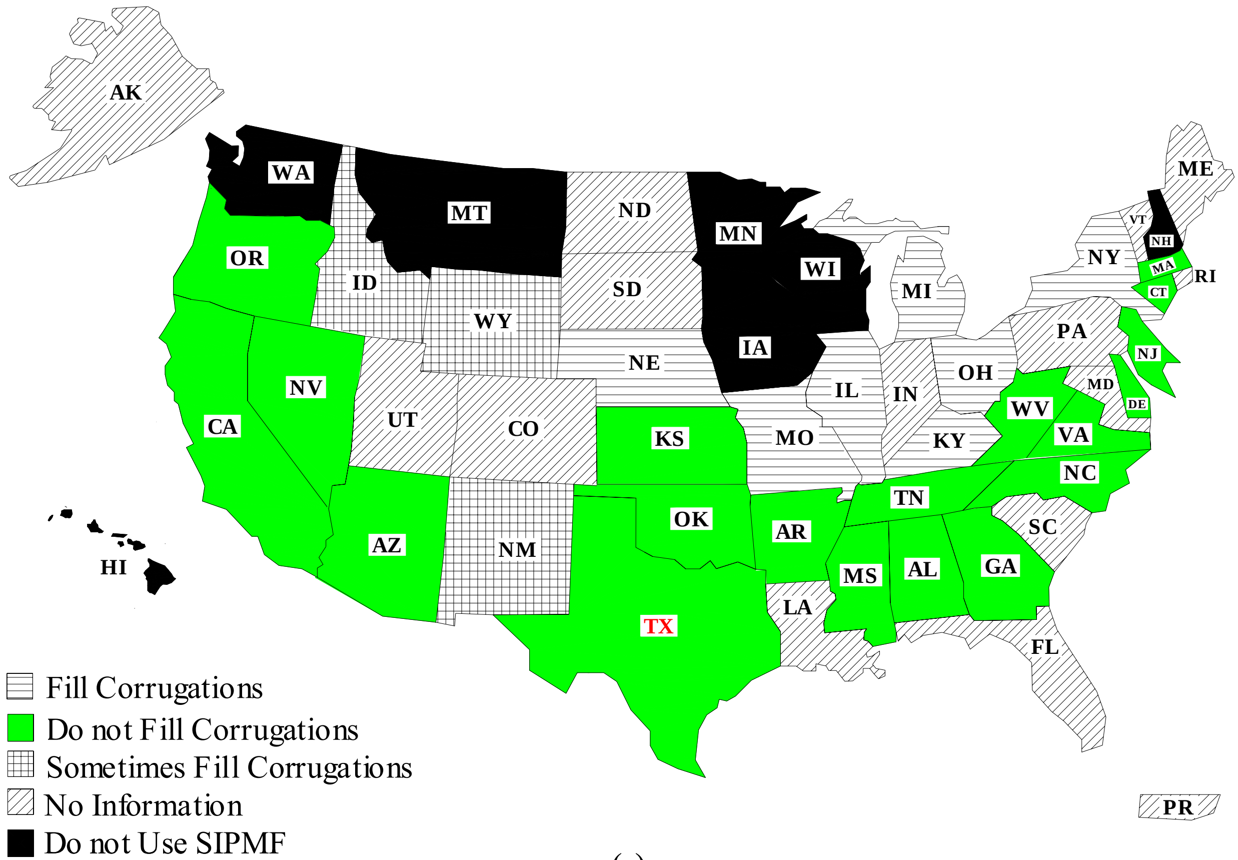
Figure 6. Is your department satisfied by the performance of SIPMF?



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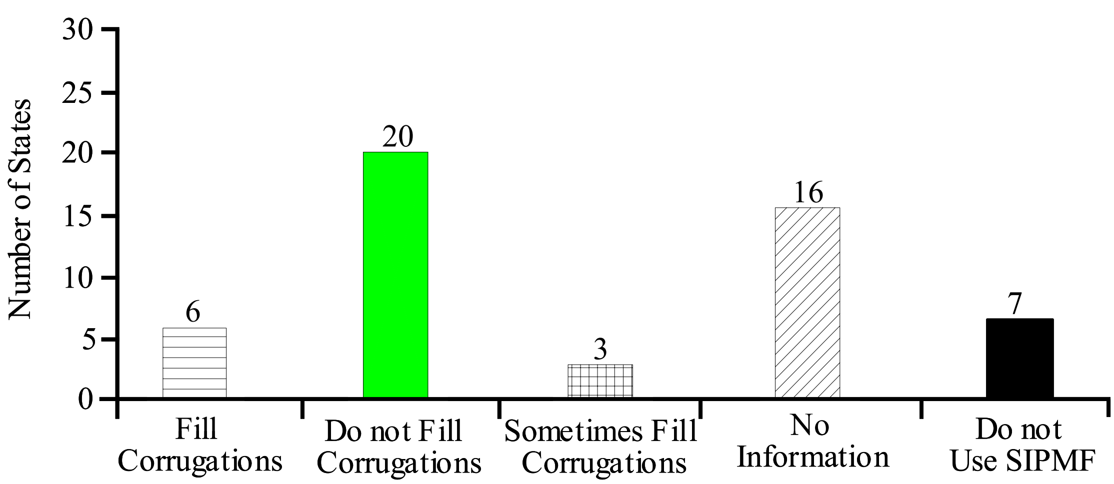

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Figure 7. Does your state fill corrugations of SIPMF with Styrofoam to reduce dead load?

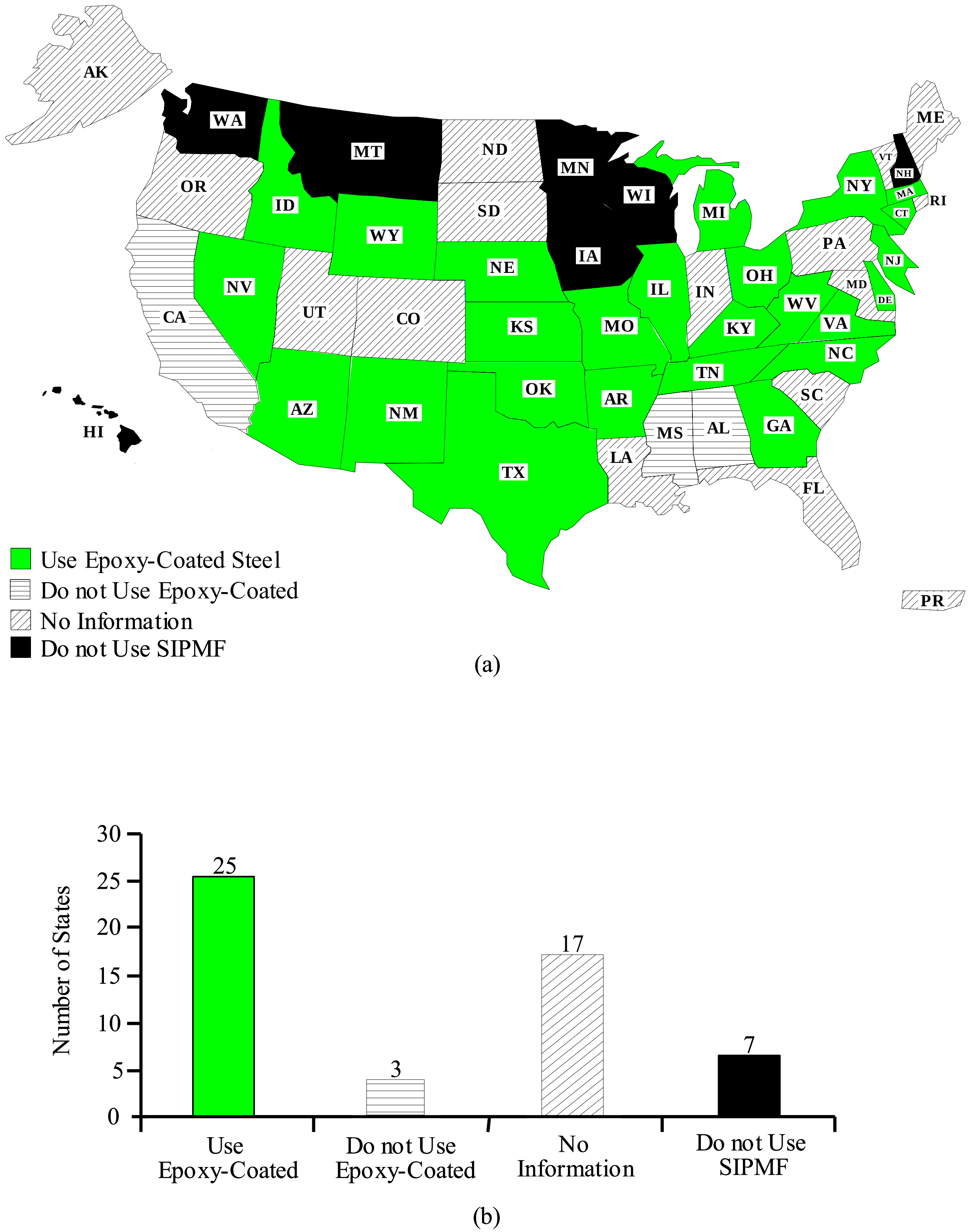


Figure 8. Does your state use epoxy-coated steel in bridges with SIPMF?

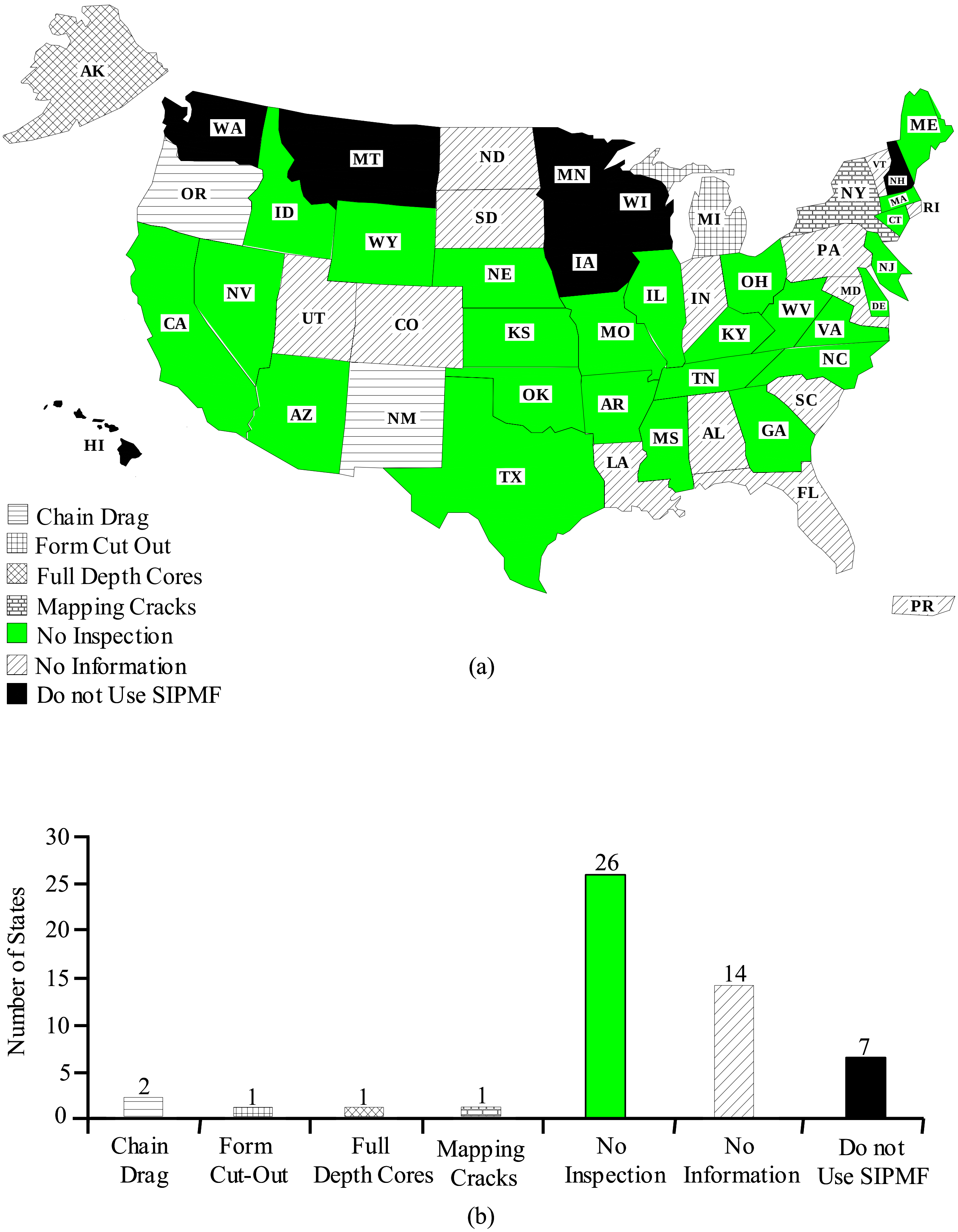
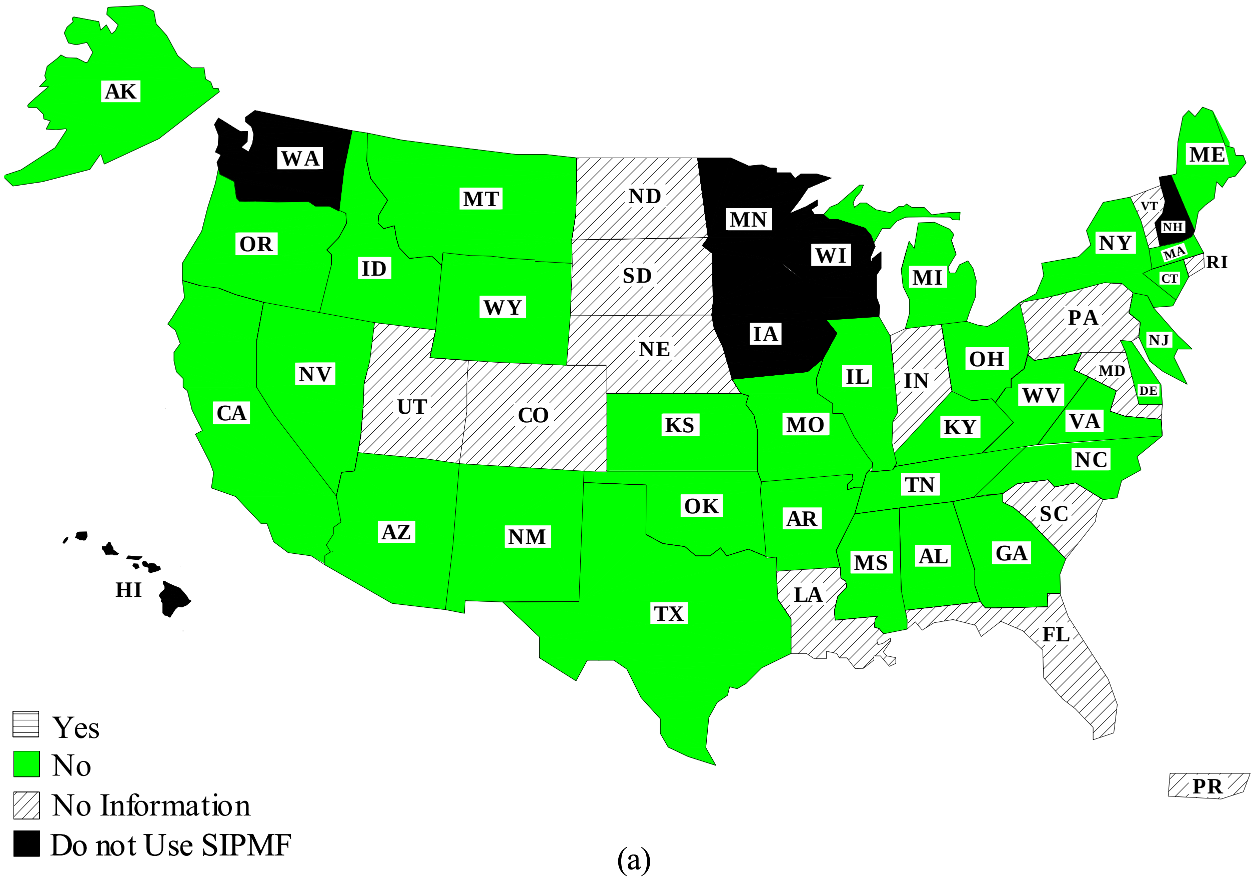


Figure 9. Beside visual inspection and hammer sounding of the surface, what other techniques does your department use to inspect SIPMF bridge decks?



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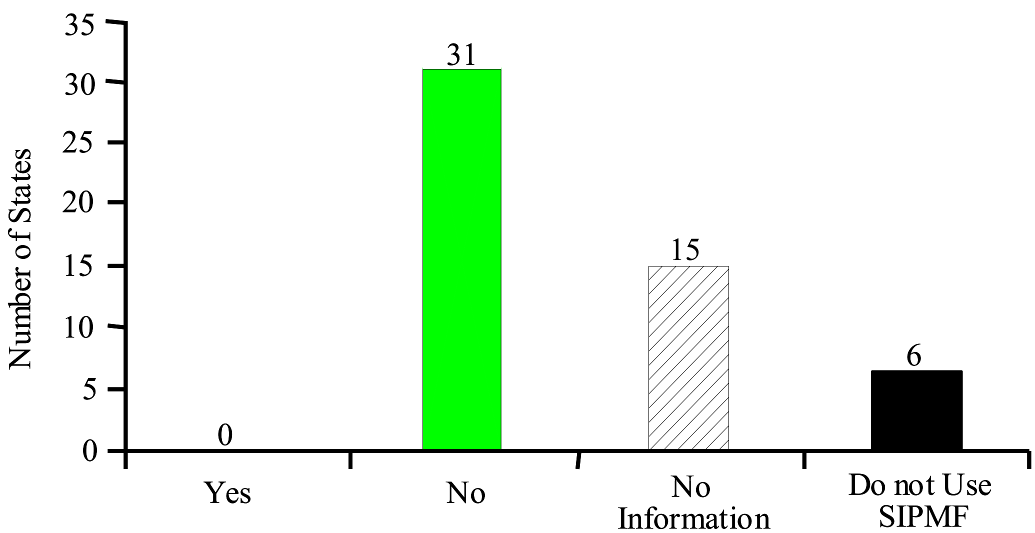

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Figure 10. Does your state gather specific data related to SIPMF bridge decks?

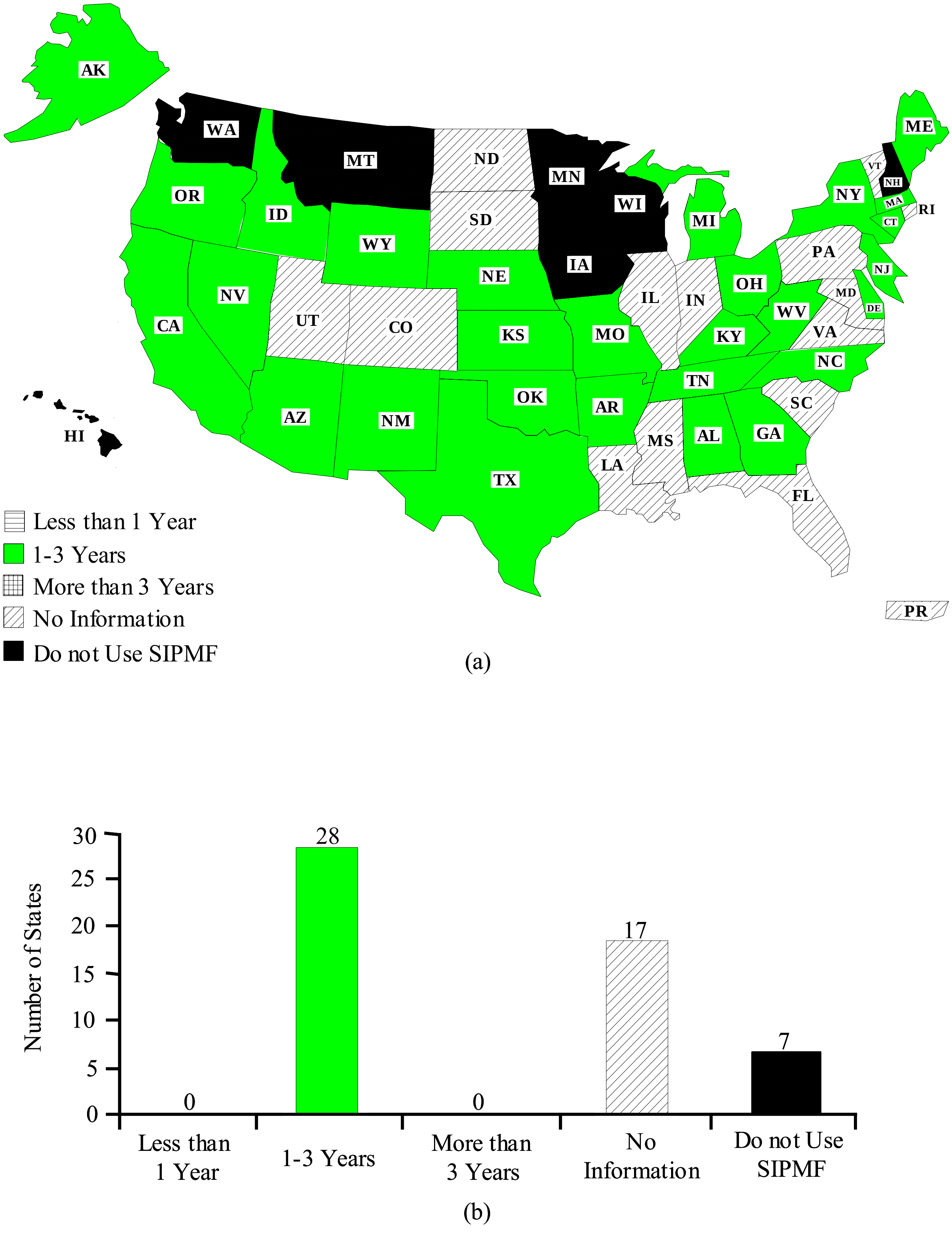

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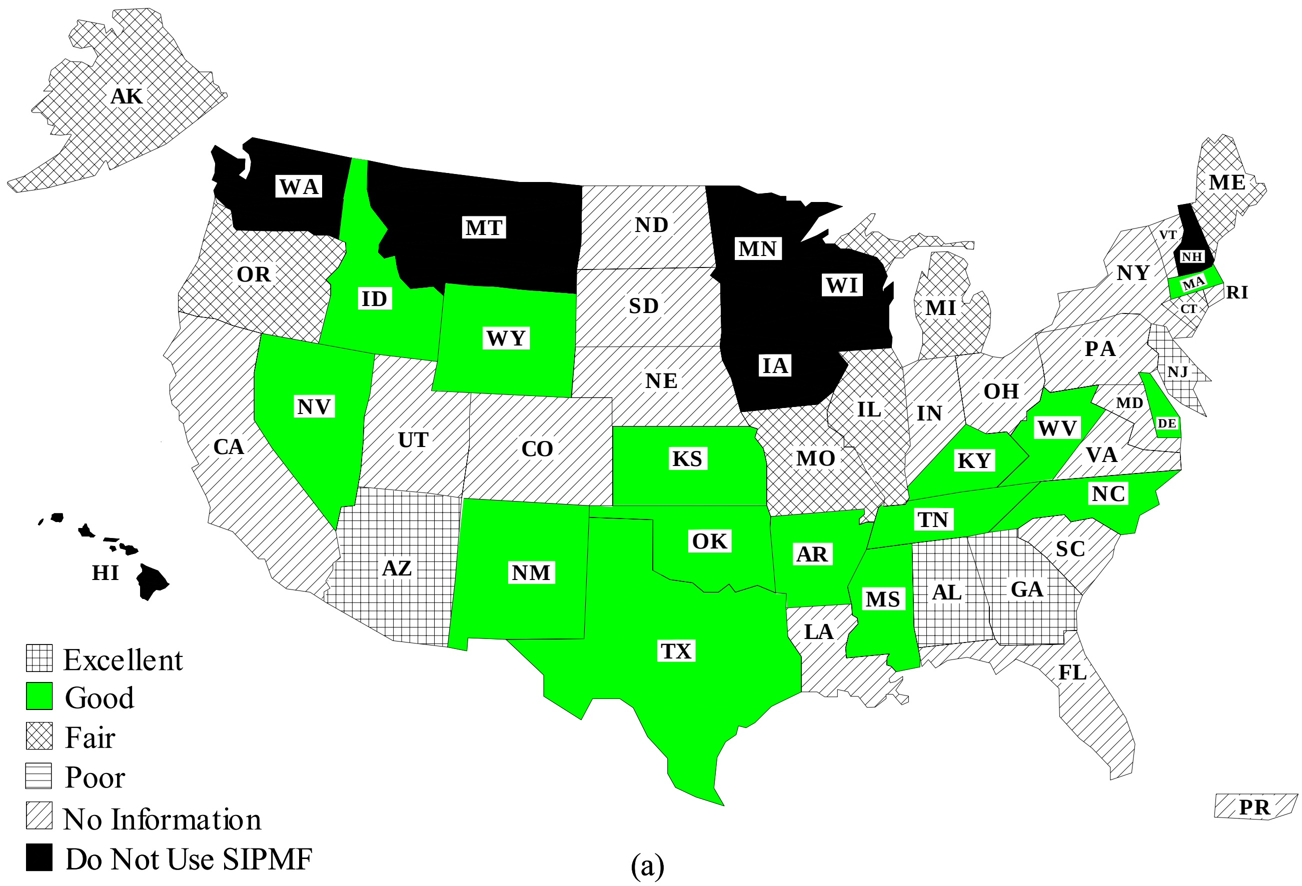
Figure 11. What is the typical period between each inspection of decks with SIPMF?



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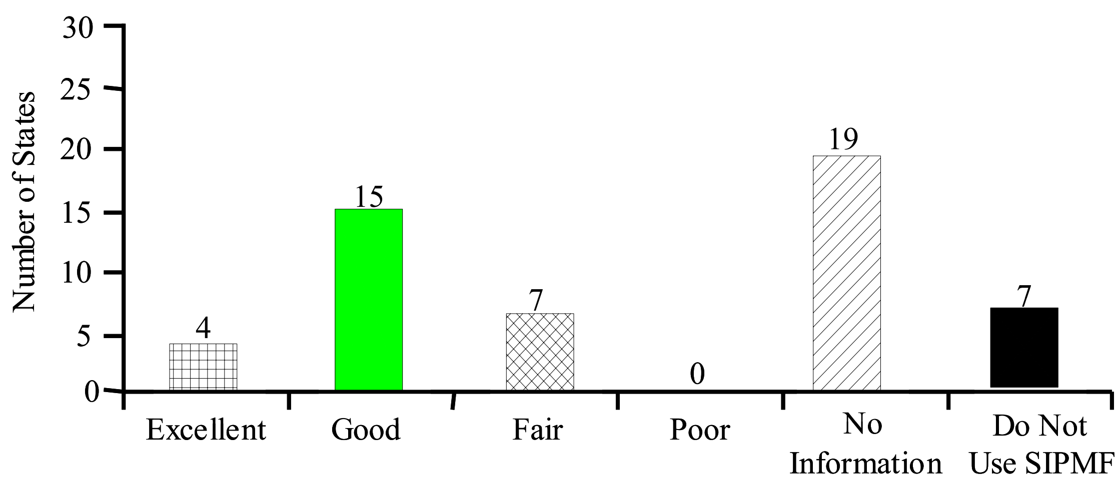

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Figure 12. How can you describe the status of SIPMF bridge decks in your state?

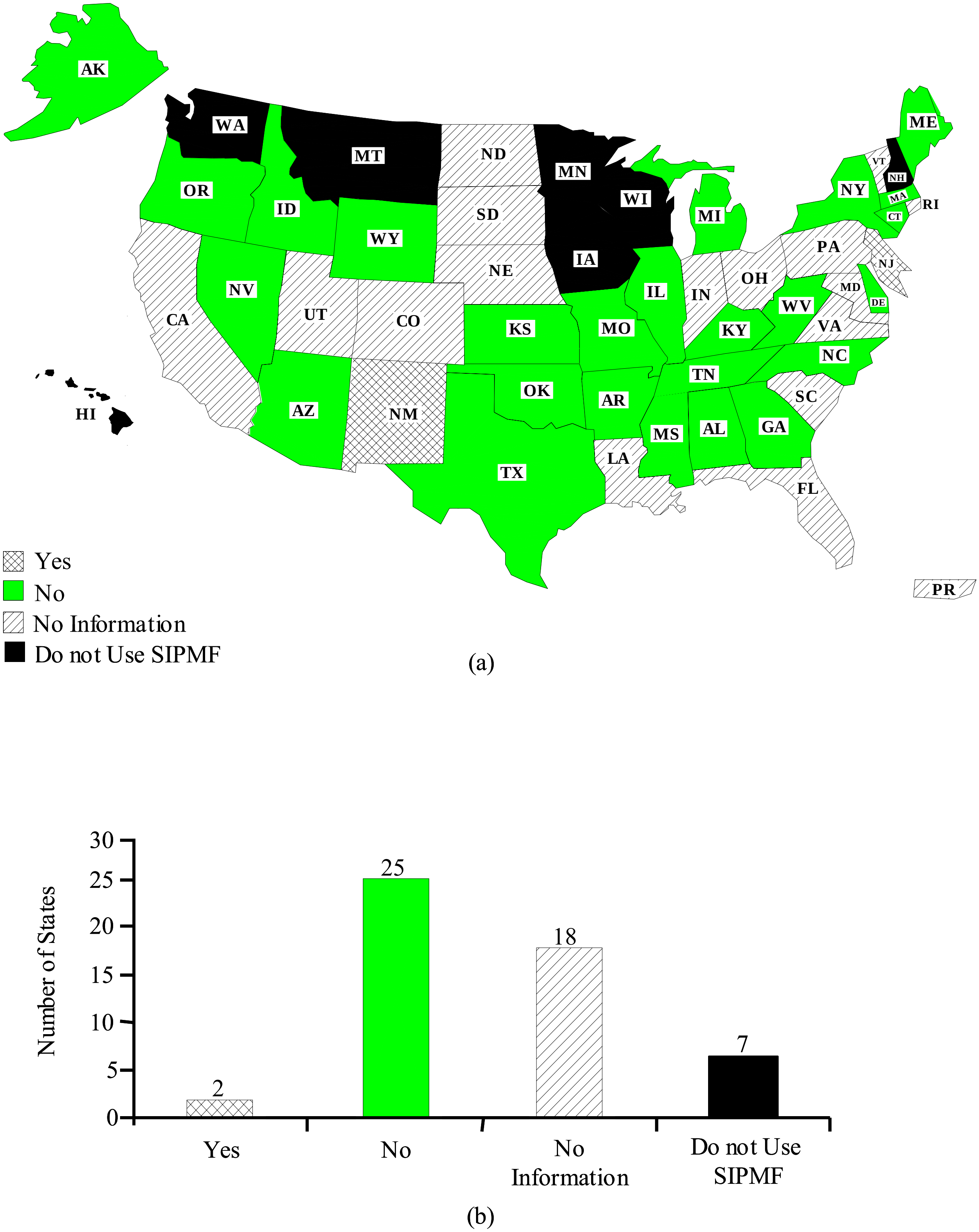
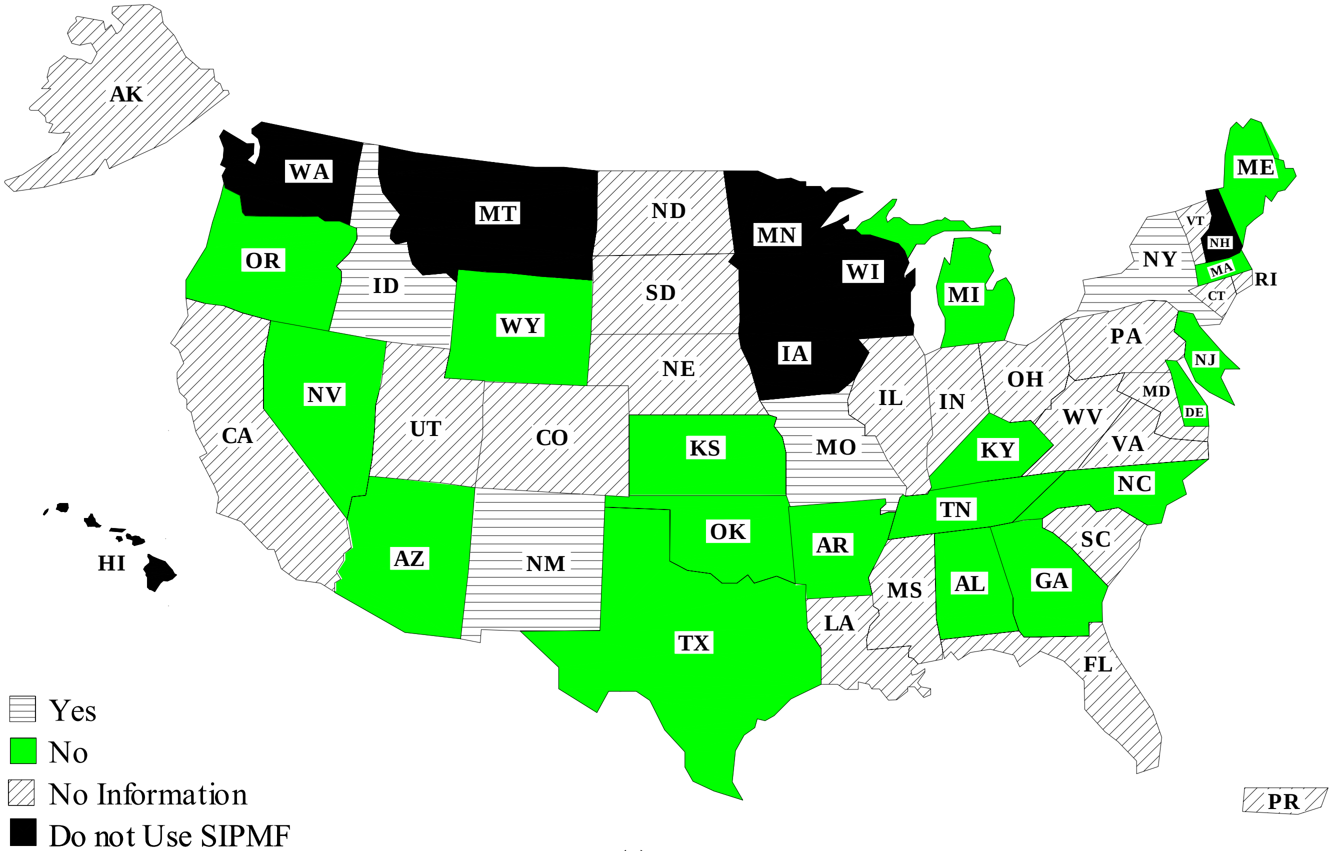


Figure 13. Do you believe that SIPMF increase the long term durability of bridge decks?



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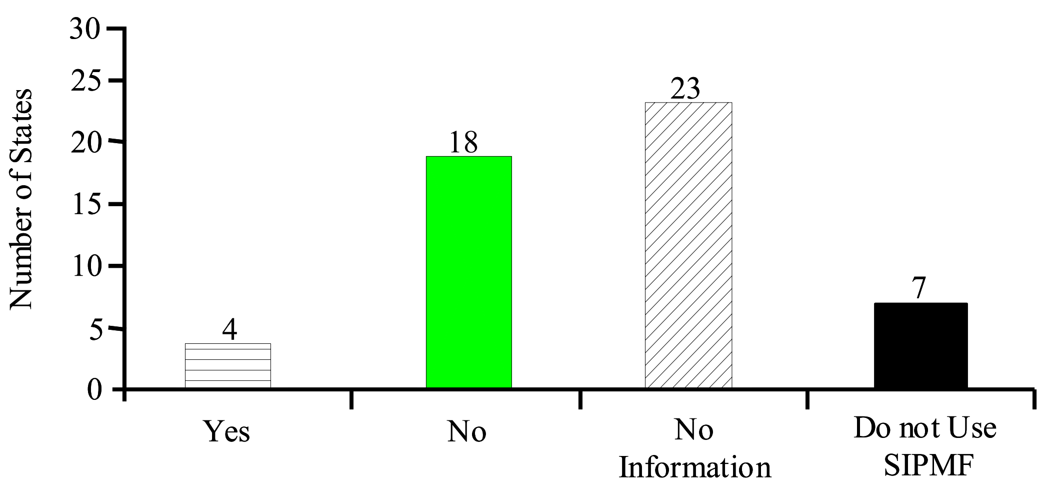

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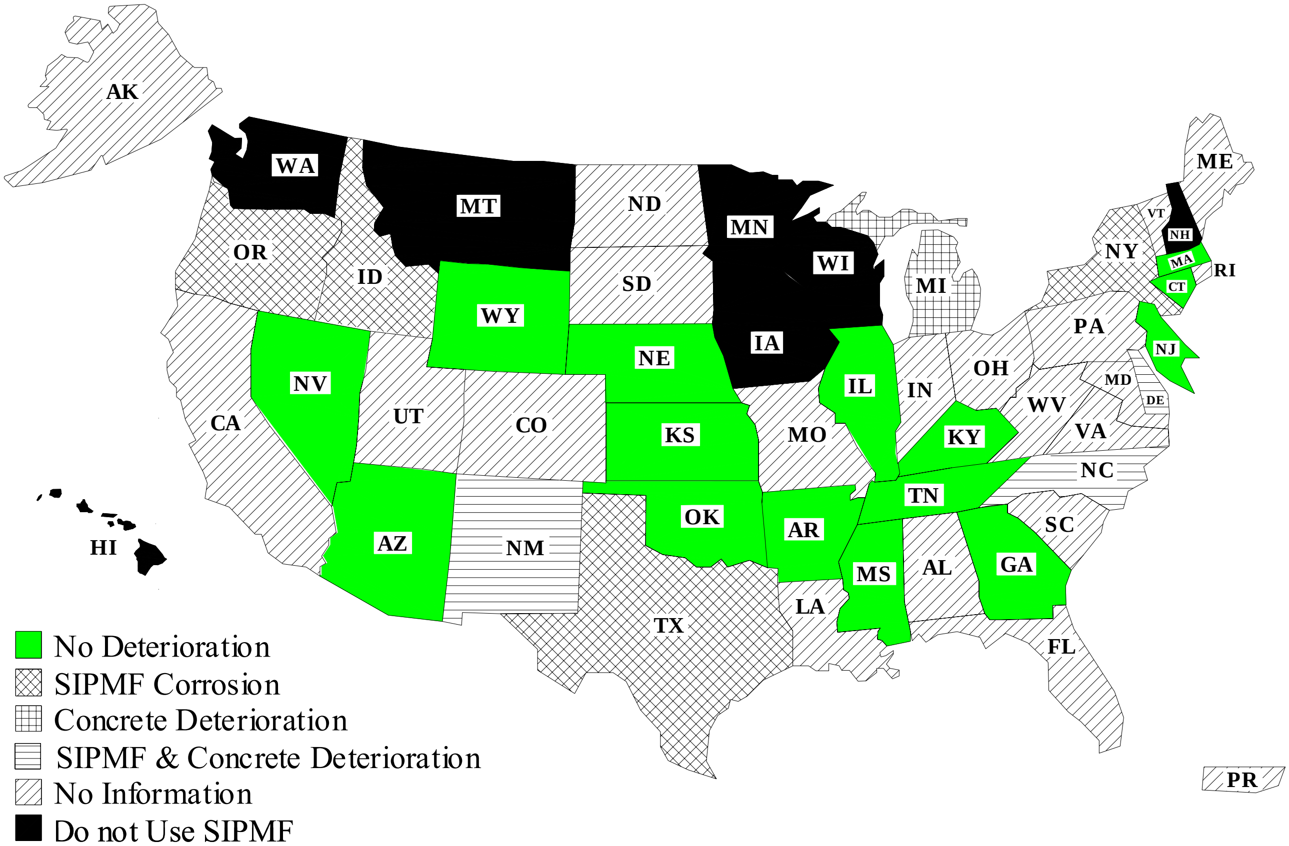
Figure 14. Has your state observed a difference in performance of decks with SIPMF constructed with bare steel reinforcement versus epoxy-coated reinforcement?



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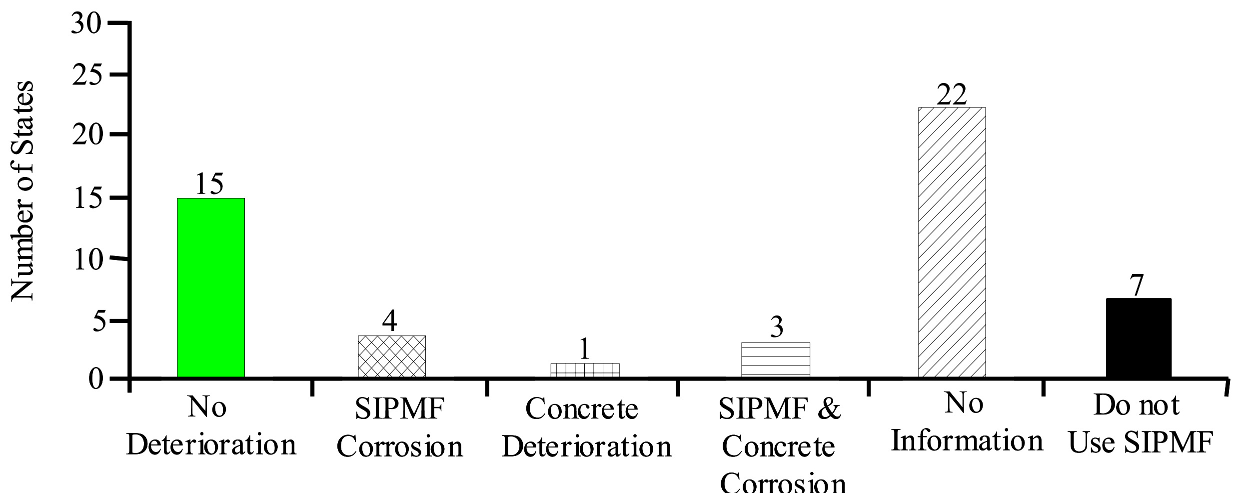

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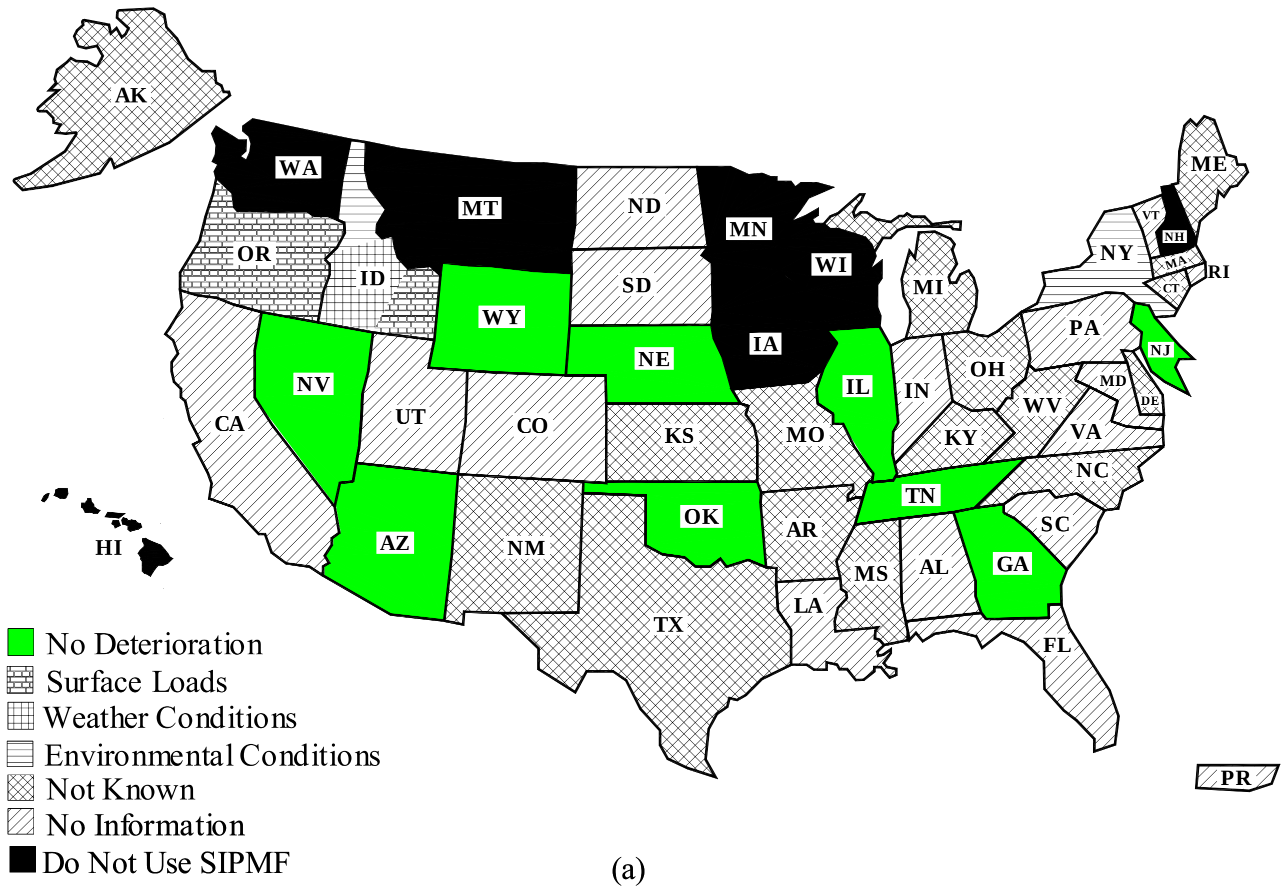
Figure 15. As a result of using SIPMF, what types of deterioration of bridge decks have been observed?



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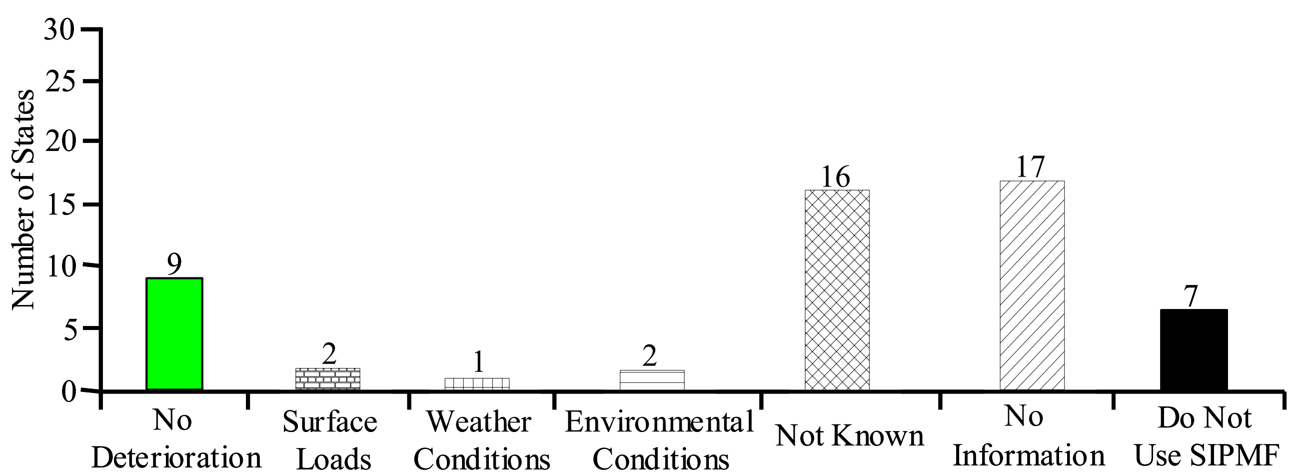

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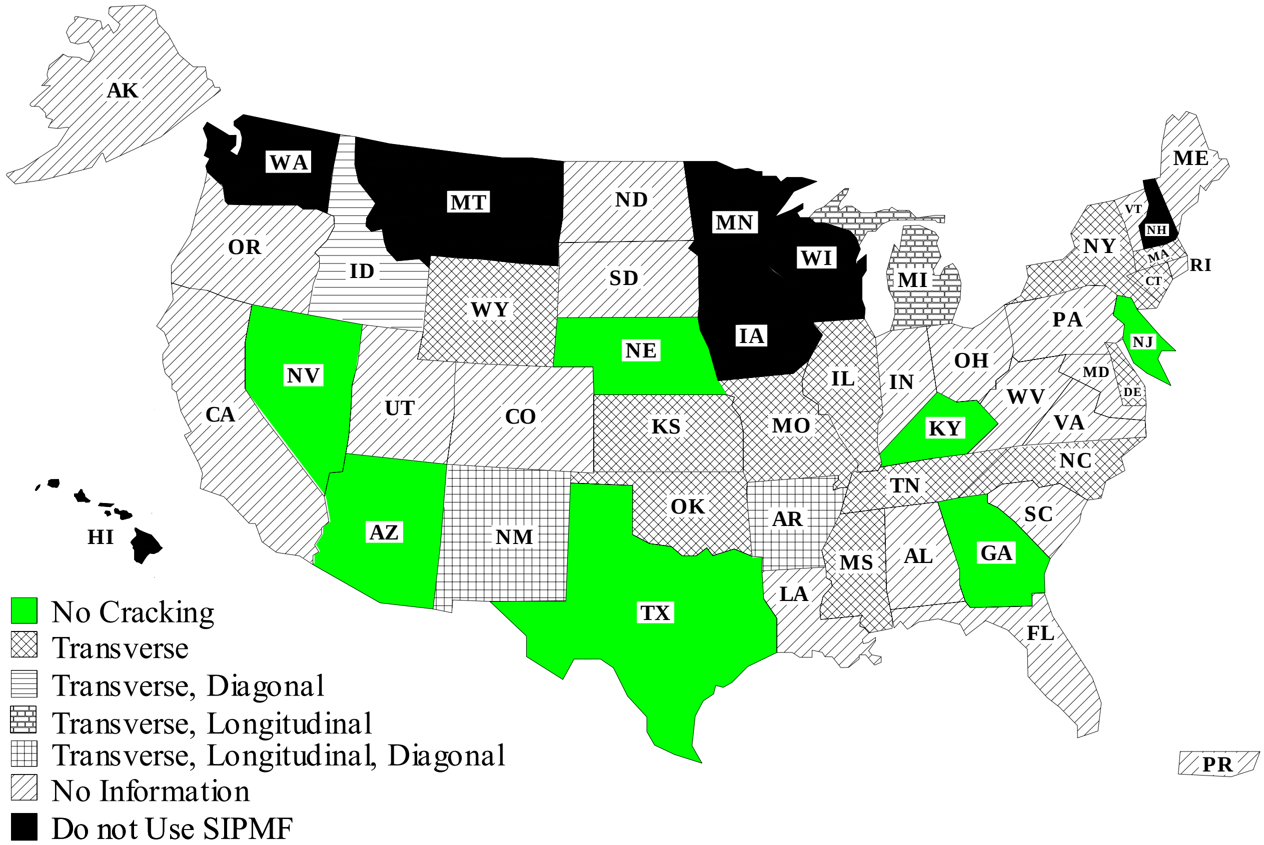
Figure 16. What is the cause of the bridge deck deteriorations when constructed using SIPMF?



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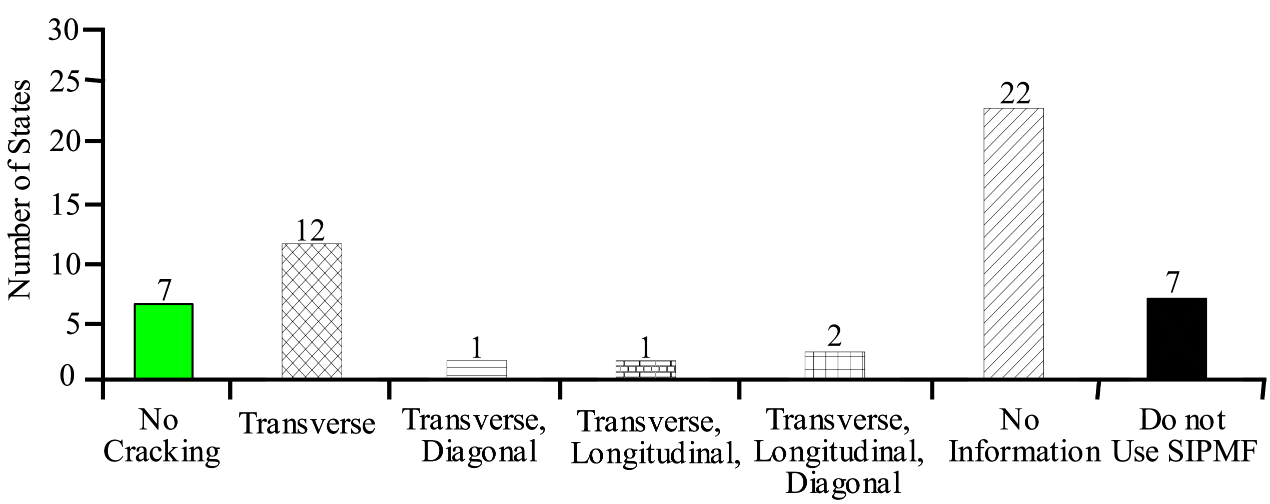
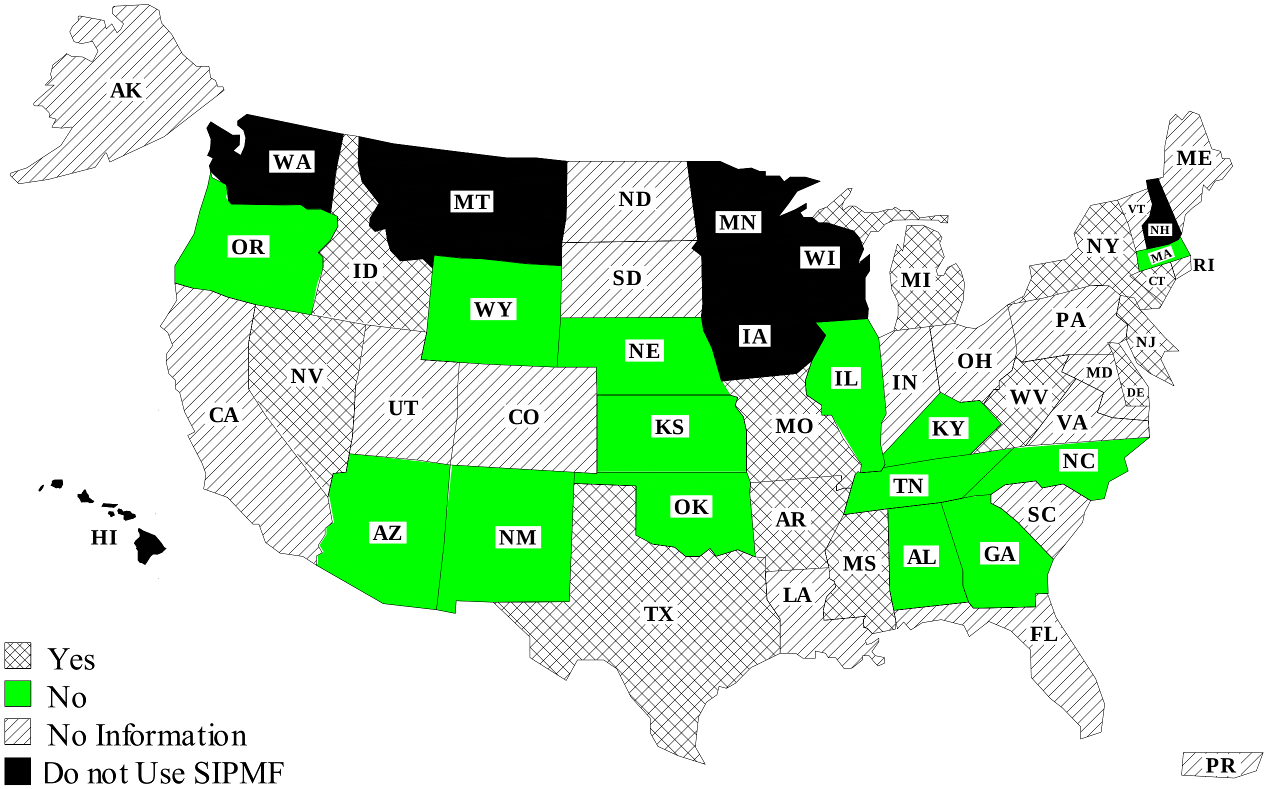


(b)

Figure 17. What is the most common type of deck cracking observed in SIPMF bridge decks?



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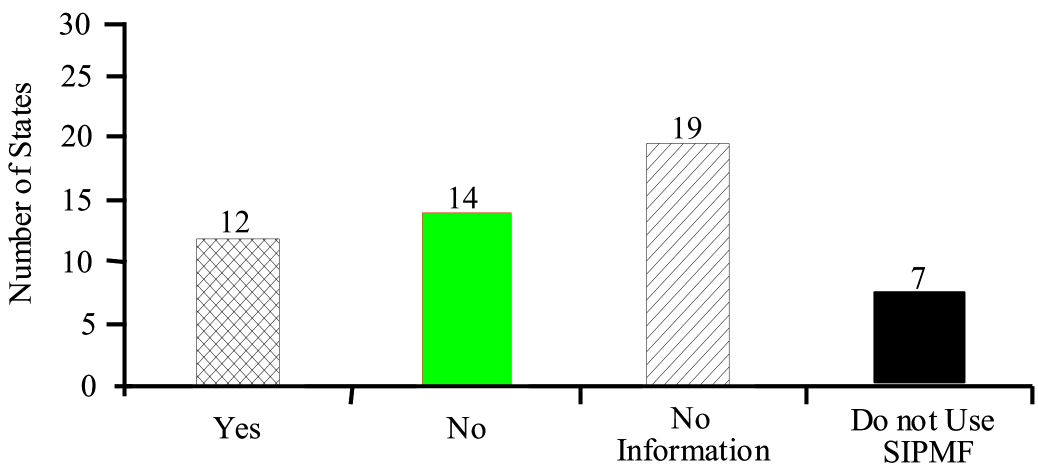

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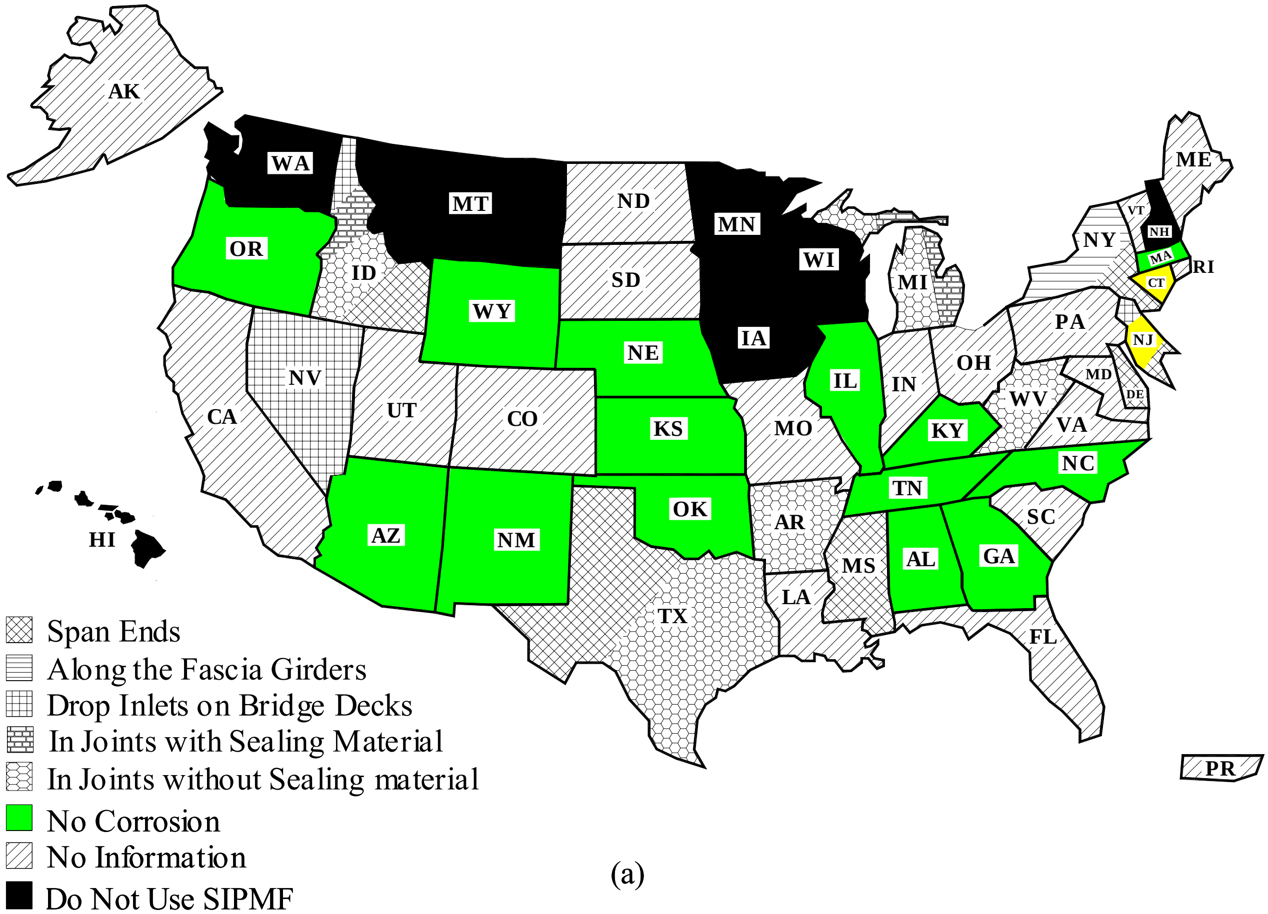
Figure 18. Has any corrosion in the SIPMF been observed?



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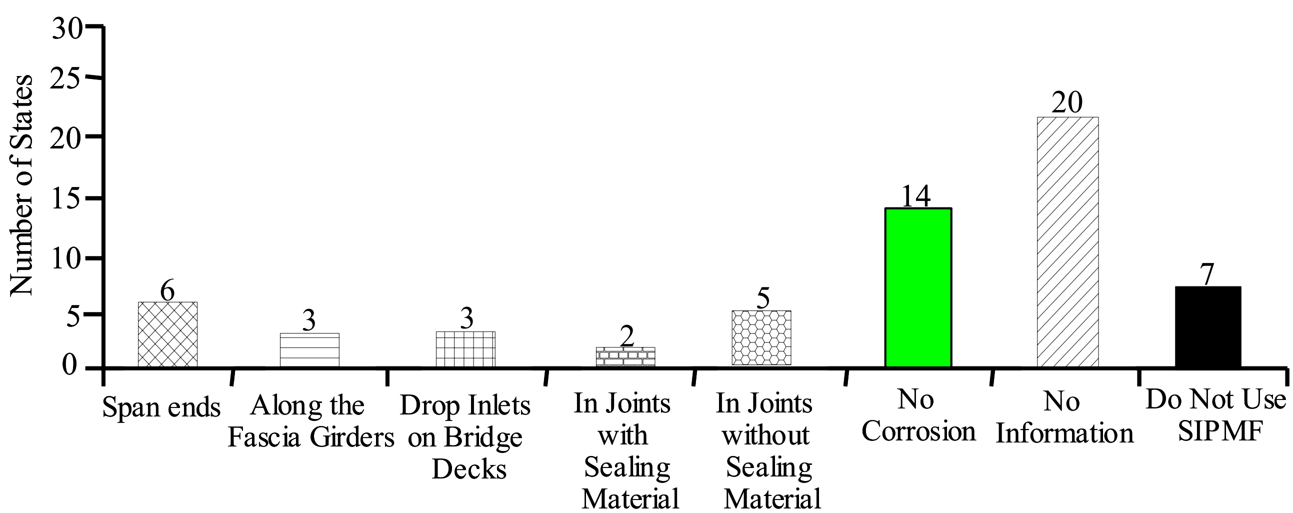
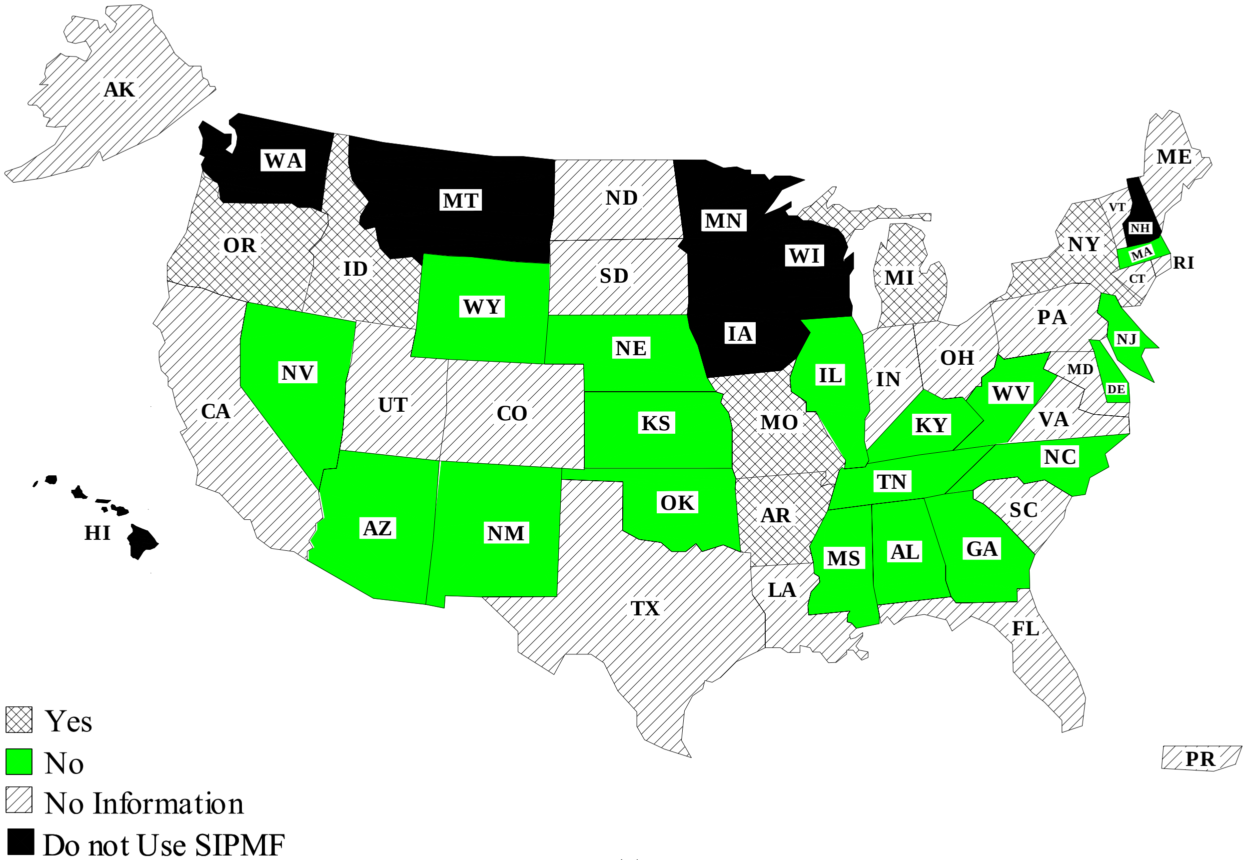


(b)

Figure 19. Where on the bridge was the most extensive corrosion of SIPMF concentrated?



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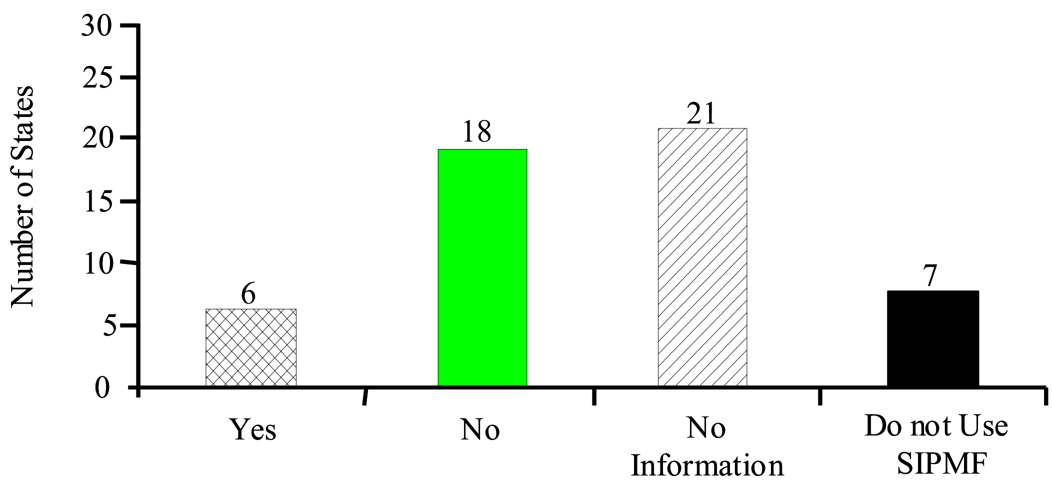
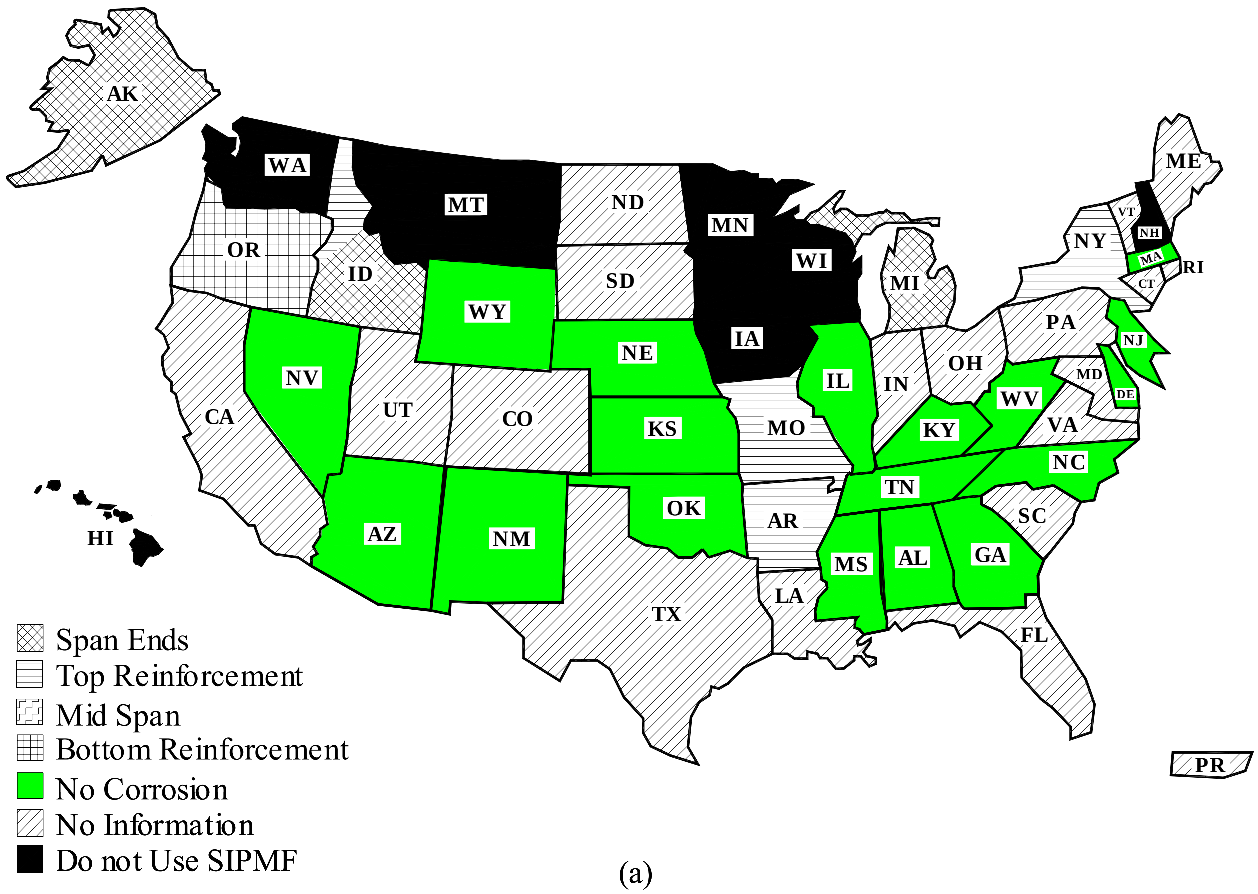
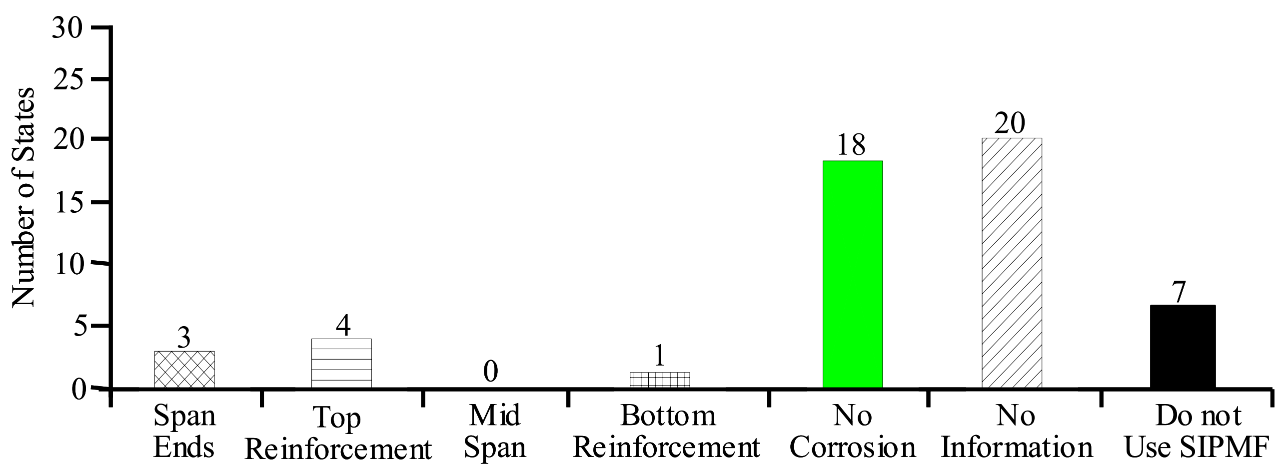


(b)

Figure 20. Is there any corrosion observed in the deck reinforcement?

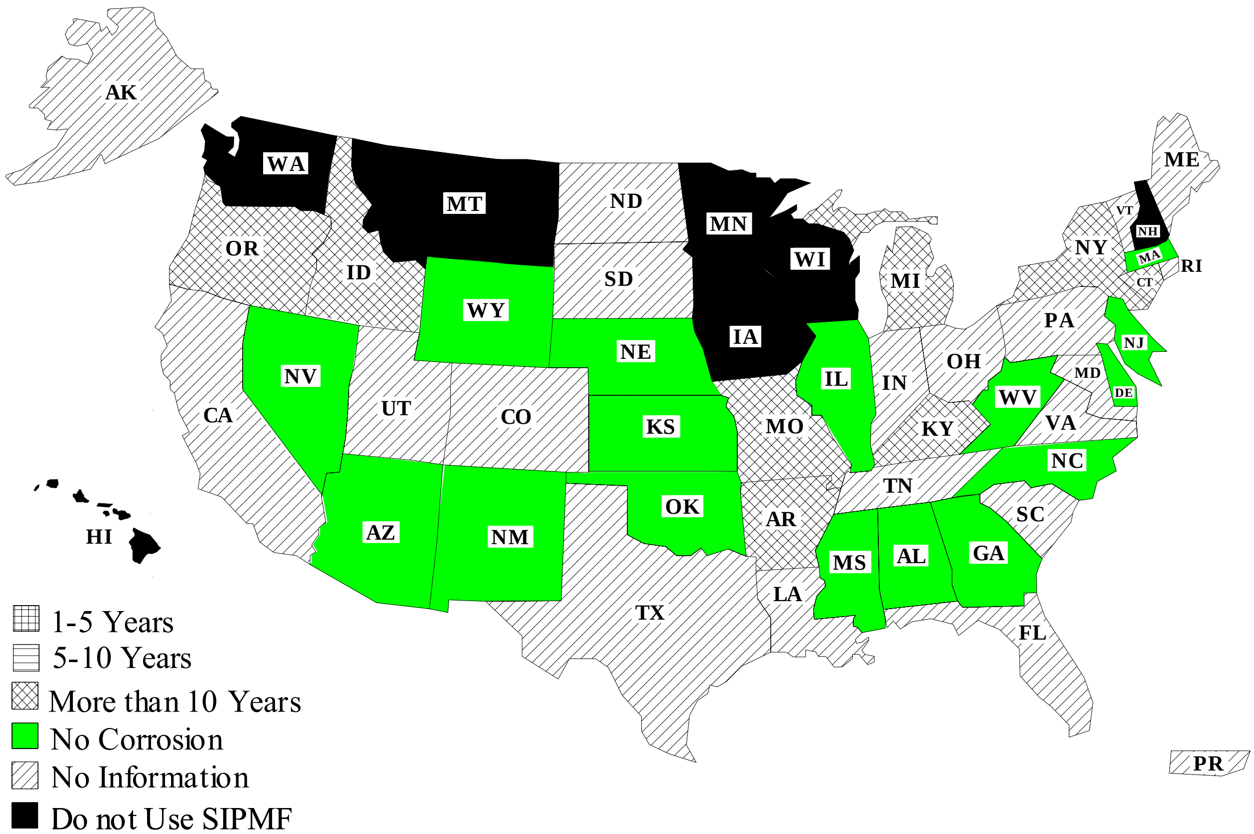


(a)

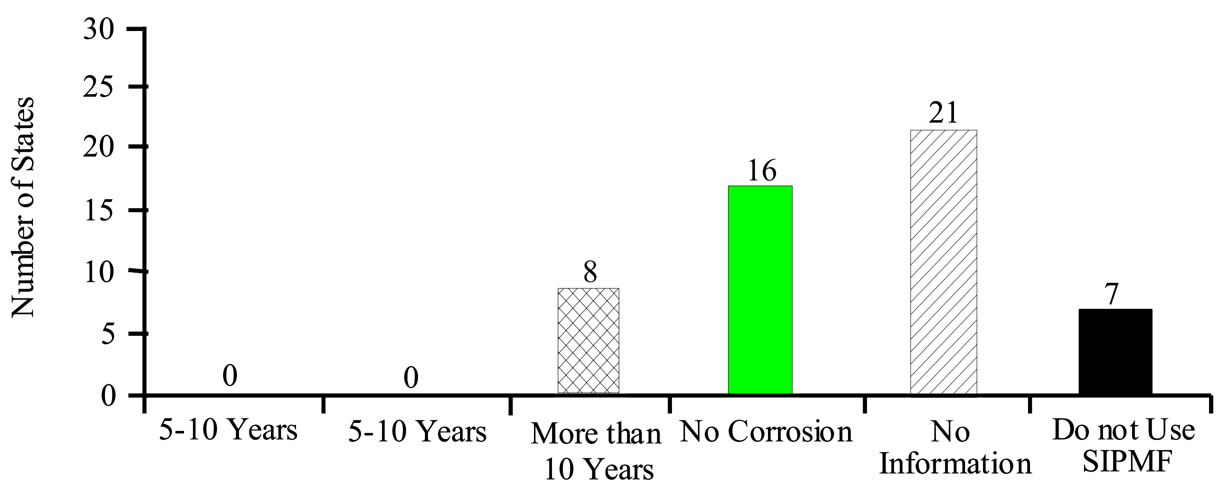


(b)

Figure 21. Where on the bridge was the most extensive corrosion of deck reinforcement concentrated?

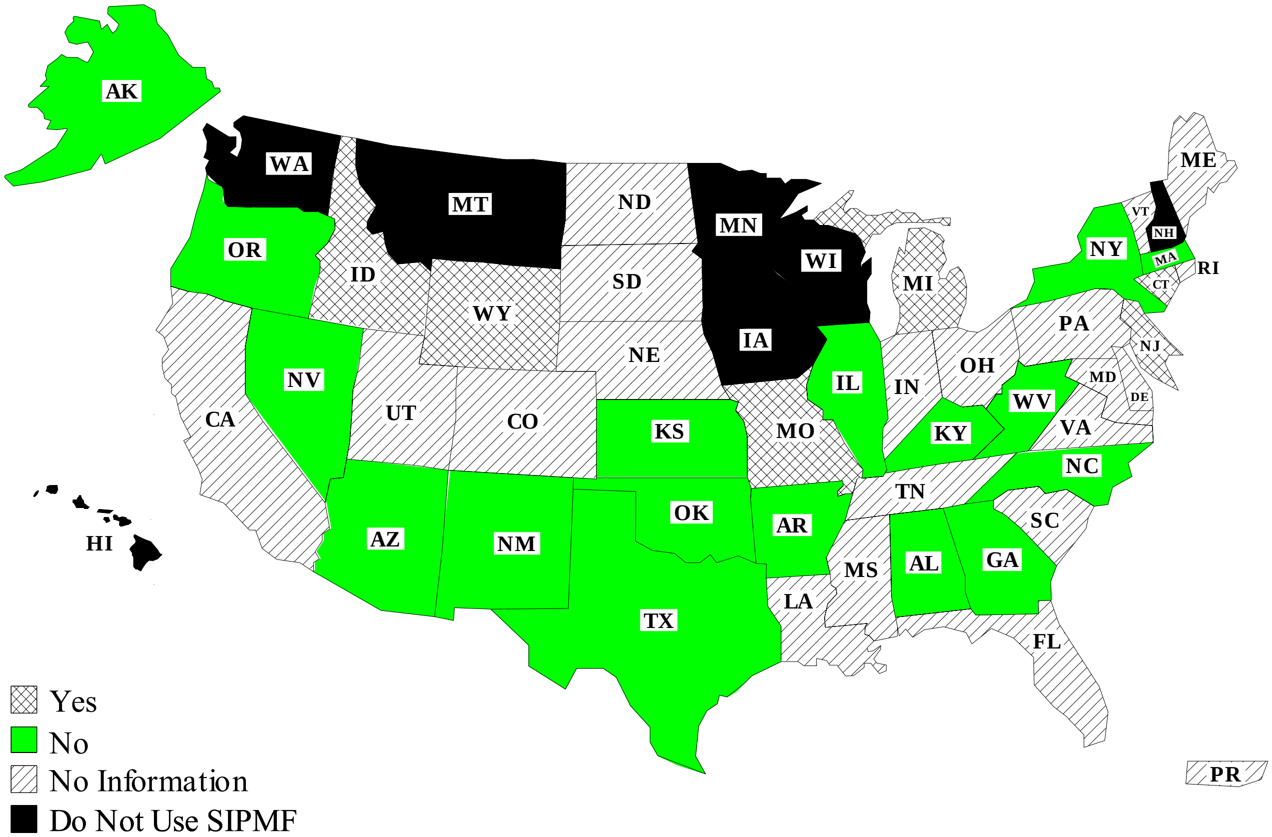


(a)

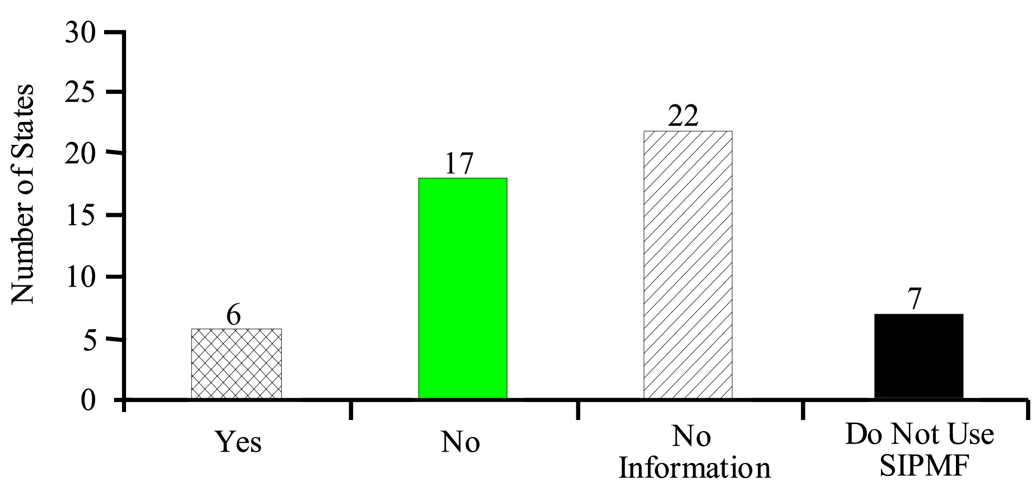


(b)

Figure 22. After how long did the extensive corrosion occur?

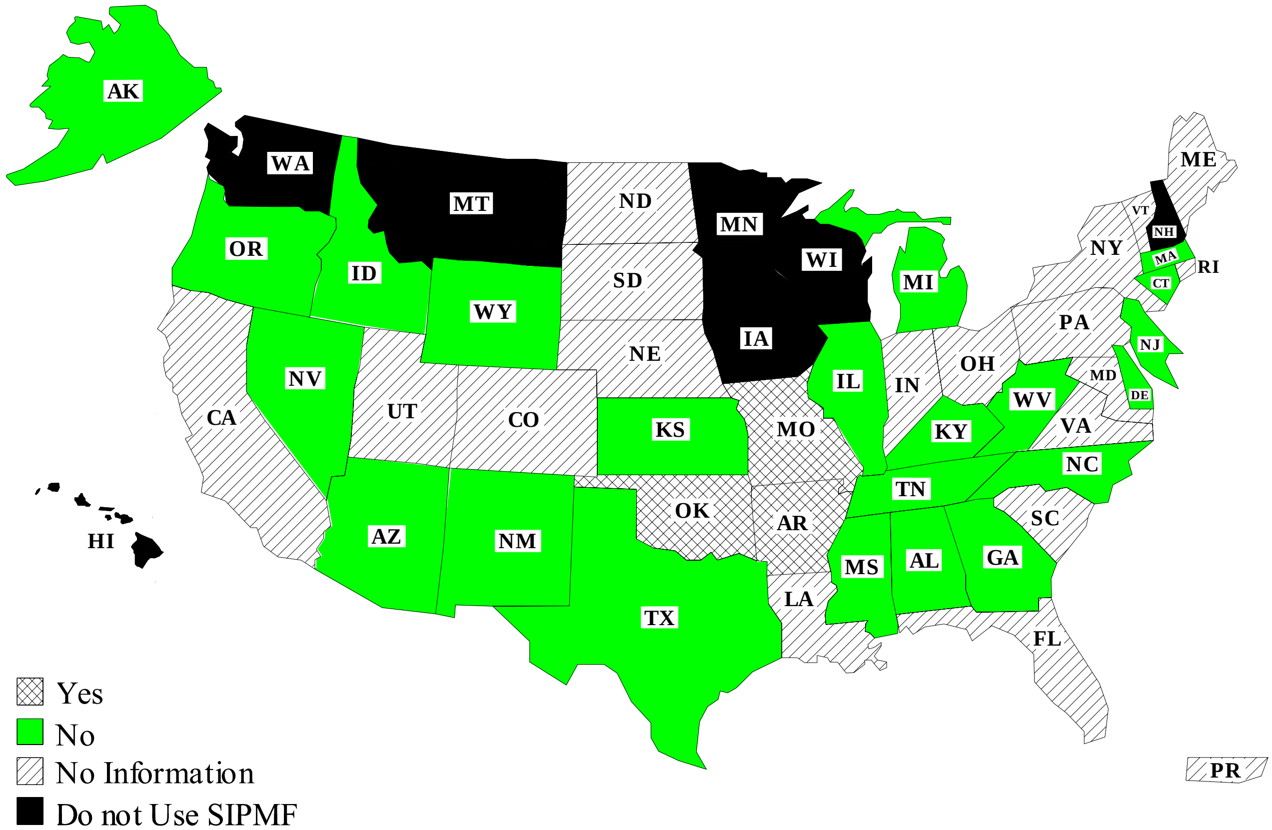


(a)

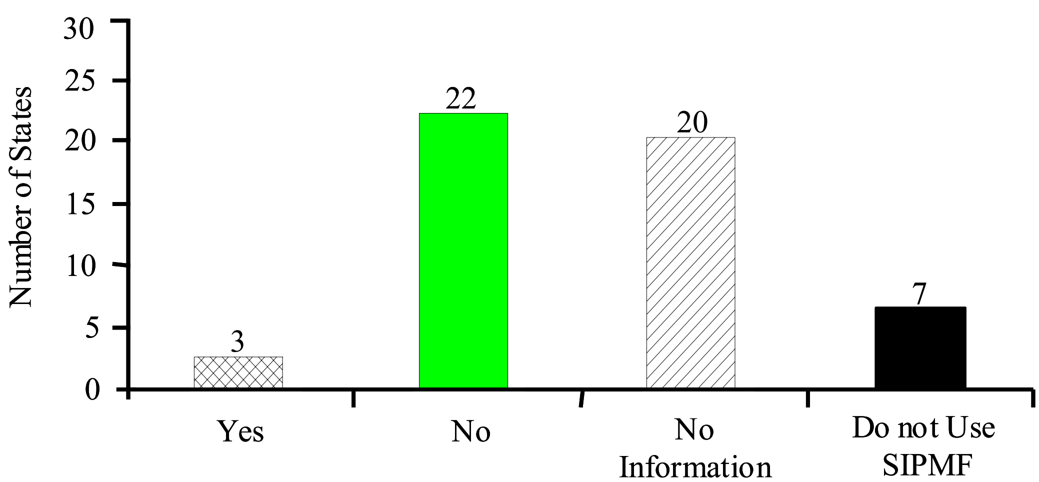


(b)

Figure 23. Has any effect of joint leakage on the SIPMF been observed?

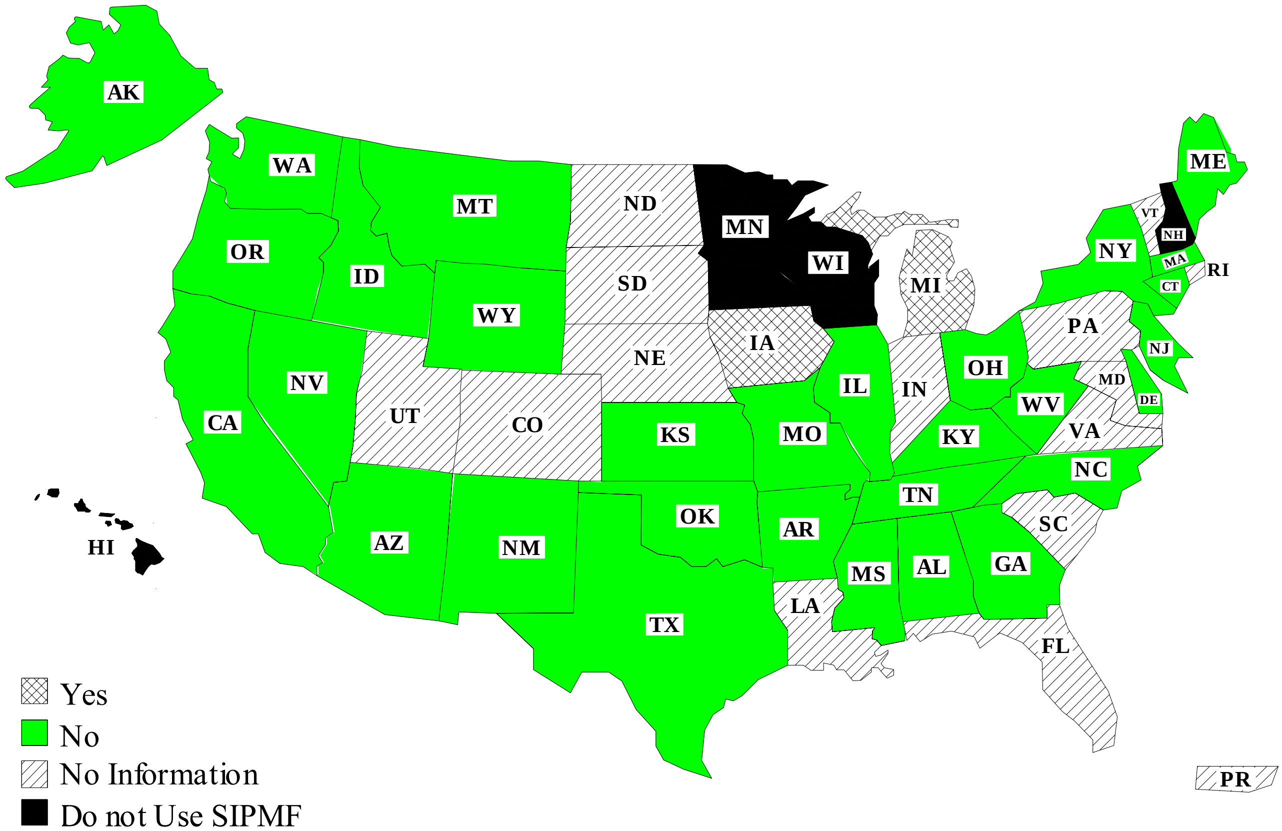


(a)

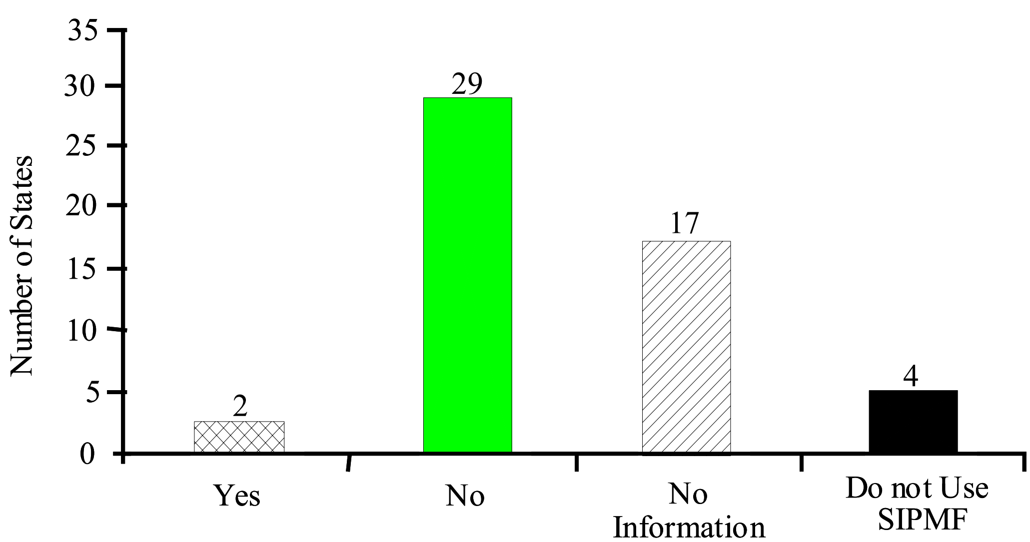


(b)

Figure 24. Were there any problems observed a direct result of using SIPMF?



(a)



(b)

Figure 25. Are you aware of any research reports in your state related to using SIPMF for bridge deck construction?

Additional Comments

State	Comment
Alabama	We have both transverse and longitudinal cracking in some of our bridge decks, but I do not attribute it to use of SIPMF. Shrinkage cracking occurs with all types of deck forms.
Arizona	Epoxy-Coated deck reinforcement is used at elevations over 5000 feet, regardless whether SIPMF are used. <u>SIPMF systems are considered for the following situations:</u> 1) When bridges span high traffic volume roadways, deep canyons or live streams. 2) When removal of conventional formwork would be difficult or hazardous. 3) When use of SIPMF system for long bridges with simple geometry could save time and/or money. 4) Where time is a critical element of the project.
California	SIPMF is not allowed on California bridges in areas where snowfall occurs. In general, on State-owned bridges (which are in the tens), the SIPMF is not included in capacity estimation. There are about tow hundred county-owned bridges in California, often single span bridges, where AC is placed directly on corrugated metals decking which acts as “forms” as well as a structure element.
Connecticut	SIPMF are only allowed over electrified rail lines or in bays over utilities where removal of conventional formwork is not feasible.
Illinois	So far our experience with SIPMF is very limited.
Maine	We have constructed only one deck with SIPMF, in 1959. It was recently replaced. We frequently use prestressed concrete slab panels in lieu of SIPMF.
Mississippi	We are concerned that with the transverse deck cracking problem we are experiencing, the use of SIPMF will contribute to premature deck deterioration due to water trapped in the forms.
Nevada	No specific cracking type (longitudinal, transverse or diagonal) has been typical of decks cast with SIPMF. Rust areas in SIPMF have typically been associated with drain cuts which have not had galvanized repairs made thereby exposing uncoated steel to drain leakage.

Figure 26. Is there any other information that you would like to share with the research team related to your experiences with observations of SIPMF?

Additional Comments

State	Comment
New Jersey	The use of SIPMF in New Jersey has been very successful with no notable deterioration of deck slabs that can be attributed to their use.
New Mexico	Since about 1990 we allowed contractors to use SIPMF or removable forms. Almost all bridges built after 1990 used SIPMF. We also require Epoxy-Coated rebar w/both mats w/SIPMF. For removable forms we require Epoxy-Coated rebar in top mat only. Contractors preferred SIPMF. Almost 100% of bridges built in New Mexico since 1990.
Ohio	We are currently examining SIPMF and trying pilot projects FY 02-06. Your research will be an important benchmark.
Oregon	When repairing a concrete deck blowout/delam using a full depth patch the delams tend to migrate outward from the original hole. The deck tends to deteriorate at an accelerated rate around the repair patch. However, when the repair included a SIPMF on the bottom side of the deck the repair seems to last much longer.
Washington	We have one state owned bridge that I know with SIPMF. The bridge was built in 1930 and rebuilt in 1949. I am assuming that the SIPMF were used in the 1949 rebuilding. This bridge is over a body of salt water and the metal forms are severely rusted out. Based on this experience as a bridge inspector, I am not in favor of ever allowing them to be used on one of our bridges.
Wyoming	Wyoming allows, but not require, the contractor to use SIPMF. We design our bridges with 15 lbs/SF additional dead load to account for the forms in most cases. However, if the actual dead load increase from filling these forms with concrete will exceed 15 lbs/SF, then the contractor is required to fill or partially fill the voids with Styrofoam. Dead load calculations not only take into account the weight of the field forms, but also the weight of additional concrete resulting from deflection of the forms, which we limit to ½ inch.

Figure 26. Is there any other information that you would like to share with the research team related to your experiences with observations of SIPMF? (Continued)

Appendix A

Survey

The Michigan Department of Transportation (MDOT) is engaged in a research project with the Structural Testing Center at Lawrence Technological University. This project involves the investigation of inspection procedures and deterioration modes of bridge decks constructed with Stay-In-Place Metal Forms (SIPMF) and epoxy-coated reinforcement.

One phase of the research program is to acquire data and experiences related to SIPMFs from state engineers representing all 50 states. Please find a survey in Word and pdf format attached to this e-mail message. Your response to this survey is important for advancing the state of practice of this bridge construction technique. The multiple choice portion of the survey can be completed electronically by clicking on the selected box.

You may either indicate your responses to the survey directly as a reply to this e-mail or as a hardcopy. Hardcopy responses should be faxed or mailed to Dr. Grace's attention at Lawrence Technological University. We anticipate this survey will take approximately 10 minutes to complete. Additional information and survey results may be obtained through Dr. Grace at Lawrence Technological University. His Contact Information is listed at the end of the attached file.

We would appreciate having the completed survey returned by March 1, 2002. Thank you for your cooperation in completing this survey.

Best Regards,

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Multi-State Survey for Practices of Departments of Transportation Related to the Inspection and Deterioration of Bridge Decks Constructed with Stay-In-Place Metal Forms (SIPMF) and Epoxy-Coated Reinforcement.

CONTACT INFORMATION

State:

Please tell us about yourself**:**

Name:

Title / position:

Department:

Telephone No:

Fax:

E-mail Address:

Mailing Address:

City:

Zip Code:

PRACTICES

1- Does your state use Stay-In- Place Metal Forms (SIPMF) for constructing deck slab bridges?

☐ Yes ☐ No

2- What is your state's policy concerning the use of permanent SIPMF?

☐ Not permitted ☐ Permitted ☐ Permitted in special situation

3- In the case that your state does not permit the use of SIPMF, please specify the reasons.

4- Approximately how many bridges having decks with SIPMF does your state have?

☐ Less than 100 ☐ From 101 To 500 ☐ From 501 to 1000 ☐ Greater than 1000

5- Approximately how long have decks with SIPMF been used by your state in bridges?

☐ 10 years or less ☐ 10-20 years ☐ 20-30 years ☐ More than 30 years

6- Is your department satisfied by the performance of SIPMF?

☐ Very satisfied ☐ Satisfied ☐ Neutral ☐ Not satisfied ☐ Very dissatisfied

7- Does your state fill corrugations of the SIPMF with Styrofoam to reduce dead load?

☐ Yes ☐ No

8- Does your state use epoxy-coated steel in bridge decks with SIPMF?

☐ Yes ☐ No

INSPECTION

9- Besides visual inspection and hammer sounding of the surface, what other techniques does your department use to inspect SIPMF bridge decks?

☐ Ultrasonic methods

☐ Acoustic Tomography

☐ Ground-Penetrating Radar

☐ Infrared Thermography

☐ Laser Crack Detection

☐Petrographic examination

☐ No inspection conducted

☐ Other Please describe:

10- Does your state gather specific data related to SIPMF bridge decks?

☐ Yes ☐ No

If yes please provide: Contact person:

Phone number:

11- What is the typical period between each inspection of decks with SIPMF?

☐ Less than 1 year ☐ From 1-3 years ☐ More than 3 years

PERFORMANCE

12- How can you describe the status of SIPMF bridge decks in your state?

☐ Excellent ☐ Good ☐ Fair ☐ Poor

13- Do you believe that SIPMFs increase the long-term durability of bridge decks?

☐ Yes ☐ No

14- Has your state observed a difference in performance of decks with SIPMF constructed with bare steel reinforcement versus epoxy-coated reinforcement?

☐ Yes ☐ No

15- As a result of using SIPMF, what types of deterioration of bridge decks have been observed?

☐ No deterioration ☐ Cracking

☐ Low surface mortar deterioration ☐ Spalling

☐ High surface mortar deterioration ☐ Popouts

☐ Scaling ☐ Delamination

☐ Rubblized concrete adjacent to form

☐ Other Please describe:

16- What is the cause of the bridge deck deteriorations when constructed using SIPMF?

☐ Surface load ☐ Weather conditions ☐ Environmental conditions ☐ Not known

Explain:

17- What is the most common type of deck cracking observed in SIPMF bridge decks?

☐ Longitudinal ☐ Transverse ☐ Diagonal

18- Has any corrosion in the SIPMF been observed?

☐ Yes ☐ No

If no, skip to question 20

19- Where on the bridge was the most extensive corrosion of SIPMF concentrated?

☐ Span ends

☐ Along the fascia girders

☐ Drop inlets on bridge decks

☐ In joints with sealing material

☐ In joints without sealing material

20- Is there any corrosion observed in the deck reinforcement?

☐ Yes ☐ No

If no, skip to question 23

21- Where on the bridge was the most extensive corrosion of deck reinforcement concentrated?

☐ Span ends

☐ Mid span

☐ Top reinforcement

☐ Bottom reinforcement

☐ Others Please describe:

22- After how long did the extensive corrosion occur?

☐ 1-5 years ☐ 5-10 years ☐ More than 10 years

23- Has any effect of joint leakage on the SIPMF been observed?

☐ Yes ☐No

If yes, please describe briefly:

24- Were there any other problems observed as a direct result of using SIPMF?

☐ Yes ☐ No

If yes, please specify this problem

REPORTS

25- Are you aware of any research reports in your state related to using SIPMF for bridge deck construction?

☐ Yes ☐ No

If yes please list or provide contact information :

OTHER COMMENTS

26- Is there any other information that you would like to share with the research team related to your experiences with observations of SIPMF?

Thank you for your time in completing the survey.

For additional information and survey results, you may contact Dr. Nabil Grace at Lawrence Technological University. His contact information is listed below.

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Lawrence Technological University
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Southfield, MI 48075
Tel: (248) 204-2556
Fax:(248) 204-2568
E- mail: Nabil@LTU.edu

APPENDIX B: PROGRAM FOR ARRIVAL TIME CALCULATION

Summary of steps to determine first arrival time from through-transmission tests (from Inci, 2001)

1. $FW_{avg.} = W_{avg.} - AW_{avg.}$
2. The waveform $FW_{avg.}$ is divided into regional division.
3. First FWavg. is divided into regions of 20 points.
4. For each region the following terms were calculated:
   i. ABS $|1^{st} – last|$ $= ABS_{20}$
   ii. Avg. (1^{st} to last) "Mean" $= M_{20}$
   iii. (Max – Min) $= MM_{20}$
   iv. Standard deviation of the region $= \sigma_{20}$
5. Same as in step 3, FWavg. is divided into regions of 40, 60, 80, ……, 1000 points.
6. Same as in step 4, each region the following terms were calculated:
   i. ABS $|1^{st} – last|$ $= ABS_{40, 60, 80,…., 1000}$
   ii. Avg. (1st to last) "Mean" $= M_{40, 60, 80,…., 1000}$
   iii. (Max – Min) $= MM_{40, 60, 80,…., 1000}$
   iv. Standard deviation of the region $= \sigma_{40, 60, 80,…., 1000}$
7. For each region division eight criteria were applied:
   i. If $M_i < [\text{ Mean of } (M_1 \rightarrow M_{i-1}) – 3 * \text{Mean of } (\sigma_1 \rightarrow \sigma_{i-1})]$
   or $M_i > [\text{ Mean of } (M_1 \rightarrow M_{i-1}) + 3 * \text{Mean of } (\sigma_1 \rightarrow \sigma_{i-1})]$,
   then the first point in region "i" will be the "time base point t1".

   ii. If $ABS_i > 4 * [\text{Mean of } (ABS_1 \rightarrow ABS_{i-1})]$,
   then the first point in region "i" will be the "time base point t_2".

   iii. If $M_i > 4 * [\text{Mean of } (M_1 \rightarrow M_{i-1})]$,
   then the first point in region "i" will be the "time base point t_3".

   iv. If $MM_i > 4 * [\text{Mean of } (MM_1 \rightarrow MM_{i-1})]$,
   then the first point in region "i" will be the "time base point t_4".

v. If $MM_i > 4 * MM_{i-1}$,

then the first point in region "i" will be the "time base point t_5".

vi. If $M_i > 4 * M_{i-1}$,

then the first point in region "i" will be the "time base point t6".

vii. If $ABS_i > 4 * ABS_{i-1}$,

then the first point in region "i" will be the "time base point t_7".

viii. If $M_i < [M_{i-1} - 3 * \sigma_{i-1}]$

or $M_i > [M_{i-1} + 3 * \sigma_{i-1}]$,

then the first point in region "i" will be the "time base point t_8".

8. After calculating all of the eight time base points for each region division, the t-base matrix (8 x 50) is built as following:
   i. Region division: 20 40 60 80…………………………………………..1000

$$\begin{pmatrix} t_1 & t_1 & t_1 & t_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_1 \\ t_2 & t_2 & t_2 & t_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_2 \\ t_3 & t_3 & t_3 & t_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_3 \\ t_4 & t_4 & t_4 & t_4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_4 \\ t_5 & t_5 & t_5 & t_5 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_5 \\ t_6 & t_6 & t_6 & t_6 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_6 \\ t_7 & t_7 & t_7 & t_7 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_7 \\ t_8 & t_8 & t_8 & t_8 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & t_8 \end{pmatrix}$$

9. The average for all time base t_i from the matrix was calculated to get "Time Base Value = t_f".
10. A "Base Region" was decided to be:
    $[(^1/_3)\, t_f \rightarrow (^2/_3)\, t_f]$
11. For the Base Region the following terms were calculated:
    i. Maximum = Max_{BR}
    ii. Minimum = Min_{BR}
    iii. Mean = M_{BR}

12. The waveform $FW_{avg.}$ is adjusted by doing the following correction:

    $FW_{new} = [\ FW_{avg.}\ -\ M_{BR}\ ]$

13. A filtration is done by taking the reading each 10 points.
14. The filtered adjusted new waveform "FW_{filt}" is inverted with respect to the x-axis to get the waveform "FW_{inv}".
15. A threshold was determined to be:

    Threshold value $Th = 1.1 * [\ Max_{BR}\ -\ Min_{BR}\ ]$

16. The arrival time is determined to be:

    t_{arr} = the first intersection point of the waveform "FW_{inv}" with the threshold value "Th".

$FW_{avg.}$	: Filtered average wave
$W_{avg.}$	: Average wave
$AW_{avg.}$	: Average air wave
ABS	: Absolute value
Avg.	: Average value
1st	: First value in the region
last	: Last value in the region
(Max – Min)	: Maximum value – minimum value

Automated Program for Calculating Arrival Time Across Entire Specimen:

```
Sub ultrasonicII()
'
' ultrasonicII Macro
' Macro recorded 9/23/2003 by Administrator
'
' Keyboard Shortcut: Ctrl+r
'

For J = 1 To 4
   Select Case J
   Case 1
      Beam = "A"

   Case 2
```

```
      Beam = "B"

   Case 3
      Beam = "C"

   Case 4
      Beam = "D"
   End Select

   Workbooks.Open Filename:= _
      "C:\MDot_WH\Project\Specimens Slices\WO-C-1\Ultrasonic Readings\Time
Values.xls"

    If J = 1 Then
      Range("B2").Select
   ElseIf J = 2 Then
      Range("B3").Select
   ElseIf J = 3 Then
      Range("B4").Select
   ElseIf J = 4 Then
      Range("B5").Select
   End If

   ActiveWorkbook.Save
   ActiveWorkbook.Close

For i = 1 To 41
'Select files A1-A41...
Application.ScreenUpdating = True
   dSource = Beam & i & ".asc"

   ChDir "C:\MDot_WH\Project\Specimens Slices\WO-C-1\Ultrasonic Readings"
   Workbooks.OpenText Filename:= _
      "C:\MDot_WH\Project\Specimens Slices\WO-C-1\Ultrasonic Readings\" &
dSource, Origin _
      :=xlWindows, StartRow:=1, DataType:=xlDelimited, TextQualifier:= _
      xlDoubleQuote, ConsecutiveDelimiter:=False, Tab:=True, Semicolon:=False, _
      Comma:=False, Space:=False, Other:=False, FieldInfo:=Array(Array(1, 1), _
      Array(2, 1))
   Columns("A:B").Select
   Selection.Copy
   Windows("Arrival time Fin.xls").Activate
   ActiveWindow.Panes(1).Activate
   Columns("A:B").Select
   ActiveSheet.Paste
   ActiveWindow.Panes(2).Activate
```

```
    Range("FT32").Select
    Application.CutCopyMode = False
    Selection.Copy
    Workbooks.Open Filename:= _
        "C:\MDot_WH\Project\Specimens Slices\WO-C-1\Ultrasonic Readings\Time
Values.xls"
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Application.CutCopyMode = False

    ActiveCell.Offset(0, 1).Select

    ActiveWorkbook.Save
    ActiveWorkbook.Close
    Windows(Beam & i & ".asc").Activate
    ActiveWorkbook.Close

Next i
Next J

End Sub
```

APPENDIX C: SALT SOLUTION COMPOSITION

Typical Composition of Instant Ocean Salt Solution at Approximate Salinity of 35ppt

Ion	Instant Ocean (ppm)	Seawater* (ppm)
Chloride	19,290	19,353
Sodium	10,780	10,781
Sulfate	2,660	2,712
Magnesium	1,320	1,284
Potassium	420	399
Calcium	400	412
Carbonate/bicarbonate	200	126
Bromide	56	67
Strontium	8.8	7.9
Boron	5.6	4.5
Fluoride	1.0	1.28
Lithium	0.3	0.173
Iodide	0.24	0.06
Barium	less than 0.04	0.014
Iron	less than 0.04	less than 0.001
Manganese	less than 0.025	less than 0.001
Chromium	less than 0.015	less than 0.001
Cobalt	less than 0.015	less than 0.001
Copper	less than 0.015	less than 0.001
Nickel	less than 0.015	less than 0.001
Selenium	less than 0.015	less than 0.001
Vanadium	less than 0.015	less than 0.002
Zinc	less than 0.015	less than 0.001
Molybdenum	less than 0.01	0.01
Aluminum	less than 0.006	less than 0.001
Lead	less than 0.005	less than 0.001
Arsenic	less than 0.004	0.002
Cadmium	less than 0.002	less than 0.001
Nitrate	None	1.8
Phosphate	None	0.2

* Data for seawater values taken from Pilson (1998).